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FIELD DEMONSTRATION OF A CENTRIFUGAL ULTRA HIGH PRESSURE (UHP) P-19

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14. ABSTRACT

The Headquarters Air Force Civil Engineer Support Agency (HQ AFCESA) is finalizing the specifications for the next generation aircraft rescue and fire fighting vehicle for deployed locations. AFRL has proven that ultra high pressure (UHP) technology improves fire fighting efficiency more than 300 percent than conventional low pressure systems. Five P-19 fire trucks were modified with a new pumping system capable of producing UHP, compressed air foam (CAF) and CAF with dry chemical. Five bases with hydrocarbon training pits were chosen to participate including Dyess, Ellsworth, Mountain Home, Davis-Monthan and Tyndall. Each base was provided with training for maintaining the new UHP pump and effective use of each fire fighting system. Two firefighters were chosen to operate the vehicle and evaluations were completed including foam quality, throw distance, pump cycle testing, limited cold weather operation and live fire testing. Several design issues were identified during testing, which were resolved during testing. Field evaluations showed that UHP technology provided improved efficiency similar to that observed under laboratory conditions. AFCESA is currently implementing this technology in new vehicle purchases.

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PREFACE

This report details field demonstration of the Ultra High Pressure (UHP) fire fighting technology that was initially researched and developed (R&D) by the Air Force Research Laboratory (AFRL) in 2002. Over the past seven years, AFRL has conducted extensive R&D to scale UHP from 10 gallons per minute (gpm) on the First Response Expeditionary (FRE) fire fighting system to the 300 gpm system used for field evaluation in this report. The ultimate goal of UHP technology was to develop a fire fighting system that exceeded the effectiveness of current technology while reducing the amount of agent needed to extinguish a burning aircraft. AFRL has shown through the careful scaling of the technology that a greater than 300% improvement in fire fighting efficiency can be obtained using UHP. This is revolutionary technology advancement.

AFRL would like to acknowledge several organizations for their contributions to this project including the Air Force Civil Engineering Support Agency, the five Air Force bases Davis-Monthan, Dyess, Ellsworth, Mountain Home, and Tyndall, W.S. Darley Co, Oshkosh Corporation, Elkhart Brass, Akron Brass and HMA Fire Apparatus. Without the support of the Air Force Civil Engineering community and the fire equipment manufacturers, this technology would not be transitioning to the commercial sector.

1.0 INTRODUCTION

1.1 Background

Headquarters Air Force Civil Engineer Support Agency (AFCESA), is finalizing the specifications for the next generation ARFF vehicle for deployed locations. The P-19 has been a highly successful Aircraft Rescue Fire Fighting (ARFF) vehicle over the years, becoming the backbone for U.S. military operations both stateside and overseas. However, this aging fleet of vehicles, built in the mid-1980’s, must be replaced in the near future, creating the need for a new fire fighting vehicle. In recent years, AFRL has pioneered the development of revolutionary concepts in fire fighting equipment, techniques and strategy that will provide the basis for new military ARFF vehicle designs. The major goal for the next generation deployable ARFF vehicle is to increase the fire fighting capability using innovative technologies with current fire fighting agents. Ultra High Pressure (UHP) technology was first investigated by AFRL in 2002 for small hydrocarbon pool and running fuel fires. Over the past six years, AFRL has proven the technology can be scaled to exceed the level of protection provided by 500 gallons per minute (gpm) systems using 2/3rds less water than conventional low pressure, high flow systems. AFRL completed prototype design and testing of a 300 gpm system with the efficiency of a system three times the size and flow.

Evaluation of UHP technology in a relevant environment reduces risk to the Air Force as the technology transitions to industry. The purpose of Phase I (AFRL-ML-TY-TR-2008-4580) was to test and evaluate the prototype six-stage centrifugal pump developed by W.S. Darley Co (Darley) on the Oshkosh Technology Demonstrator (TD). The purpose of this effort (Phase II) was to demonstrate the five modified A/S32P-19 (P-19) fire trucks to include UHP water/foam, Compressed Air Foam (CAF) and Dry Chemical (DC) delivery systems at five different Air Force bases. The trucks were evaluated for reliability of the UHP pump and associated equipment; fire fighting effectiveness using Air Force firefighters versus AFRL fire technicians who have extensive UHP experience; and ease of operation for firefighters in the field that have never used UHP technology.

Results from Phase II were analyzed to validate AFRL’s Phase I results and conclusions from an operator's perspective. The Air Force Fire Chief and the Fire Chiefs at the Major Air Commands have observed multiple demonstrations of the UHP technology and agreed that substantial improvement in the efficiency of fire fighting agent has been achieved. The demonstration information can be used by the Air Force Fire Chief to provide specifications for the next generation of ARFF vehicles, including the replacement for the deployable P-19.

1.2 Scope

This report provides a summary of the results of the demonstration AFRL performed on the UHP fire fighting system and details of the field evaluations at five Air Force bases of five modified A/S32P-19 (P-19) fire trucks (UHP P-19c) to include UHP water, CAF and Dry Chemical delivery systems.

1.3 Objective

The objective of the field trials was to demonstrate UHP and the new pump technology reliability, fire fighting effectiveness and ease of operation for firefighters in the field. The Air Force bases chosen for this program were Davis-Monthan (DM), Dyess (D), Ellsworth (E), Mountain Home (MH) and Tyndall (T). This report documents discharge distance, expansion ratio, drain time and extinguishment performance for the 300 gpm UHP turret, the 20 gpm UHP handline, the 300 gpm Hydro-Chem™ turret and the 45 gpm Hydro-Chem™ handline. Fire suppression tests were conducted to demonstrate extinguishment time and agent use for firefighters in the field versus efficiencies demonstrated in a more controlled laboratory environment. The modification and field demonstrations of each of the fire trucks validated UHP for a new future vehicle buy using these technologies.

Although 121 live fire tests were performed to obtain as much objective data as possible, all subjectivity could not be eliminated due to variations in conditions such as wind, humidity and temperature during the test fires. Therefore to compensate for a lack of statistical confidence, the mature technology was put through rigid performance testing at five different installations by functional experts (firefighters).

2.0 PHASE I; OSHKOSH TECHNOLOGY DEMONSTRATOR VEHICLE TESTING SUMMARY

In May 2006, AFRL entered into a Cooperative Research and Development Agreement (CRADA) with Oshkosh to modify an existing fire vehicle platform (Technology Demonstrator-TD) to develop a dual agent 300 gallons per minute (gpm) UHP/CAF fire truck using a single centrifugal pump. Previous work by AFRL/RXQD used reciprocating pumps to produce the required pressure and flow. Typically fire trucks use centrifugal pumps because they are smaller, simpler in design and ultimately more reliable in the field. This TD was designed and modified by Oshkosh to incorporate centrifugal pumps and the CAF system. The pump was developed from a concept originated by W. S. Darley & Co. (Darley), a longstanding provider of fire pumps and associated equipment. Evaluation of a Centrifugal Pump System for Ultra High Pressure and Compressed Air Foam Fire Fighting[3] (AFRL-RX-TY-TR-2008-4580) provides detailed test methods and data. A summary of the vehicle design, conclusions and recommendations is provided as background for the subsequent field evaluations of the five modified UHP-19s.

2.1 Phase I Vehicle Description

The platform chosen for the CRADA program was an Oshkosh T-1500 fire truck (Figure 1) with a 540 horsepower Detroit Diesel engine, power divider with two power take-offs (PTO), with pump and roll capability referred to as the Technology Demonstrator (TD). Modifications made by Oshkosh to the TD included installation of the UHP system, the CAF system, a combined UHP/CAF bumper turret, UHP and CAF handlines, and associated instrumentation and controls.

Figure 1. The Technology Demonstrator

A new six-stage centrifugal pump (Figure 2) was designed and built by W. S. Darley & Co. (Darley) and Oshkosh specifically for this project recognizing that this technology could revolutionize ARFF. The centrifugal pump provided a simpler, more compact and less expensive pumping system than the plunger pump system previously used on the plunger pump UHP P-19 (UHP P-19p) developed by AFRL/RXQD. The UHP P-19p was developed as a proof of concept system using commercial-off-the-shelf (COTS) components exclusively. The COTS components used were a centrifugal pump and three UHP CAT PUMP plunger pumps. Power was supplied to each of these four pumps using a separate hydraulic motor and hydraulic pump. These components (Figure 3) were located in the engine compartment, along the left side of the chassis, and behind the water tank. In comparison, the TD used a single centrifugal pump that was shaft driven from the power divider. The TD's centrifugal pump fit in a compact package along the left side of the truck chassis. The three plunger pumps for the UHP P-19p cost $15,699.67 each[4]. The hydraulic motors, pumps, hoses, hydraulic tank, hydraulic control system, and hydraulic pump belt drive increase the cost of the total system to approximately $85,000. The single Darley UHP centrifugal pump that replaced these items was estimated to cost $25,000[5]. In addition to the cost savings, the new centrifugal pump allowed room on the TD (and later the UHP P-19c) for the original 1000 gallon water tank and provided a pump similar in design to the original centrifugal pump found on the P-19, which provided familiarity to vehicle maintenance personnel.

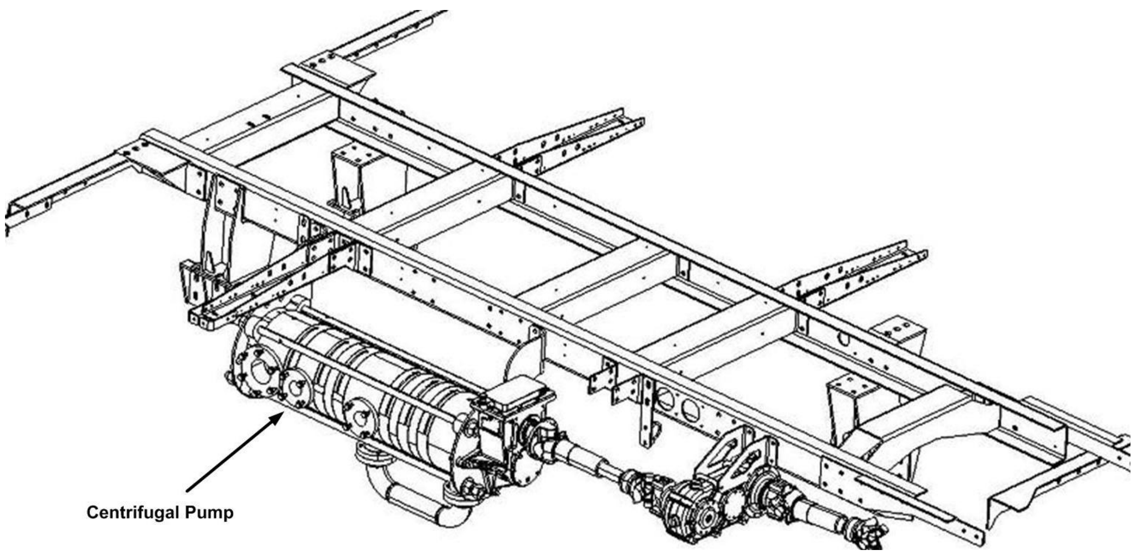


Figure 2. TD Centrifugal Pump Installation for UHP P-19c

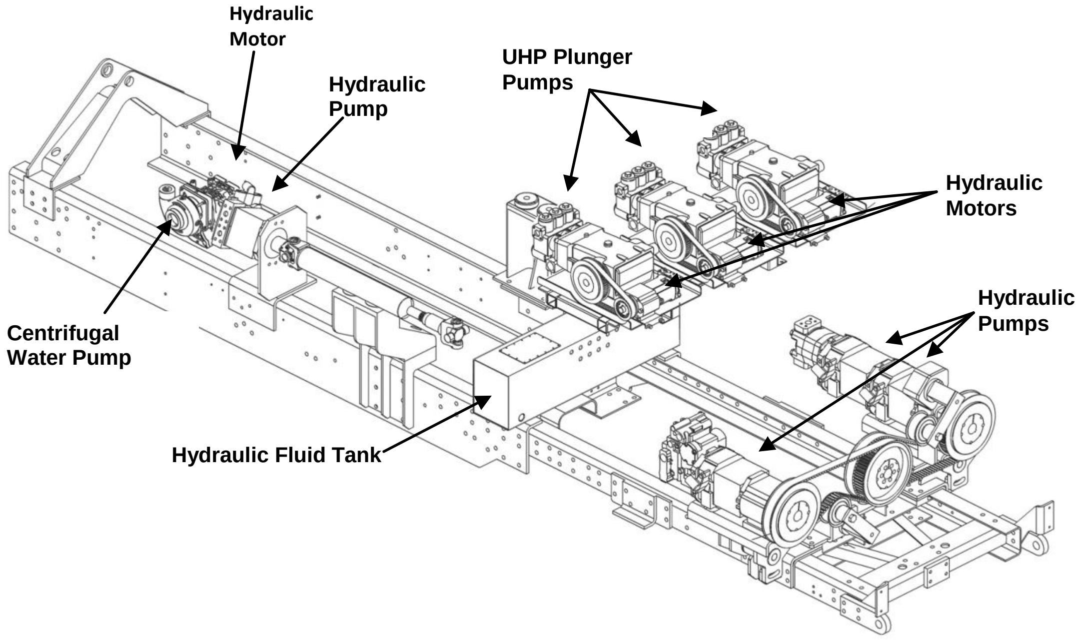


Figure 3. Pumping System and Hydraulic Drive for UHP P-19p

2.2 Phase I Testing

The truck was delivered to the AFRL/RXQD to perform experiments/testing for foam quality, discharge distance and extinguishment evaluations. These tests were prematurely terminated due to failure of the new centrifugal pump that was the result of reusing a snap ring. Although no design changes were required to correct this failure, testing was discontinued. From the tests that were accomplished, the performance indicated that the centrifugal pump could supply the pressure and flow previously demonstrated using the piston pump technology.

2.3 Phase I Conclusions

1. The TD showed promise that the centrifugal pump configuration could provide the fire fighting capabilities established in the program goals and NFPA 412 requirements, particularly with the UHP system.

2. The performance of the UHP turret provided greater pressure and flow than the program goals. Expansion ratio, drain times and discharge distance met requirements in NFPA 412. Extinguishment using the TD used less agent than that the standard P-19 as determined during the Fire Extinguishing Effectiveness Testing[6] (FEET).

3. The UHP handline on the TD was modified due to firefighter concerns about reaction force, ultimately resulting in decreased pressure, flow and discharge distance because the orifice was inserted at the hose reel instead of internal to the nozzle itself. The TD was equipped with a nozzle orifice that could not be adjusted. If a nozzle with the appropriate orifice size were available, the reaction force could have been reduced without significantly impacting nozzle pressure and discharge distance. The expansion ratio demonstrated by the TD

handline was greater than the value required by NFPA 412. Fire extinguishment efficiency exceeded NFPA requirements, indicating a reduction in agent used.

4. The CAF turret also met the requirement for flow, but did not meet the pressure requirement. There were no CAF fires conducted with the TD because of the pump failure.

5. The pump failure was the result of reusing snap rings during repeated assembly and disassembly procedures. The design of the pump was not defective, and it would not have failed if new snap rings had been installed. The five pumps tested in the P-19 retrofit program used new snap rings and no failures were experienced.

2.4 Phase I Recommendations

1. AFCESA should continue with the P-19 Retrofit Program and AFRL should evaluate the performance of the five trucks to validate that preproduction units can meet specifications under field conditions.

2. The poppet foam system should be replaced with a system that meets the foam proportioning requirements for each of the four discharge systems.

3. Continue reliability testing on the Darley pump to determine life cycle costs and mean time between failures.

4. Additional tests should be conducted on system pressure, flow and fire extinguishment to provide statistical information with at least 90% confidence levels.

3.0 PHASE II; FIELD DEMONSTRATION OF FIVE MODIFIED P-19'S SUMMARY

3.1 UHP P-19c Demonstration Locations

Five Air Force bases were chosen based on their ability to conduct testing of the prototype vehicles using JP-8 hydrocarbon fuel for live fire testing. The bases are also located throughout the United States and offer a variety of environments, weather conditions and fire pit configurations. The Air Force bases chosen for this program include Davis-Monthan, Dyess, Ellsworth, Mountain Home and Tyndall.

3.2 Training

AFRL provided training on each UHP modified P-19 vehicle upon delivery from Oshkosh. The firefighters who extinguished the fires were provided with classroom instruction and hands-on training from AFRL personnel with their modified UHP P-19c vehicle to gain a level of comfort with the capabilities, limitations and differences in the vehicle versus a standard P-19. Oshkosh provided training to the vehicle maintenance personnel upon delivery of the vehicle, including maintenance of the new fire fighting system, basic troubleshooting and repairs. Oshkosh provided an overview of the major systems, how they functioned, maintenance items, the frequency of maintenance, and contact information for the fire department and vehicle maintenance personnel in the event of a problem. Each base was provided with a supplemental manual to describe the modifications to the vehicle.

3.3 UHP P-19c Field Demonstration Overview

The field demonstrations consisted of system checkout to assure the function of the pump, turrets, handlines and pressures for each foam system; and foam quality including foam proportioning, fire extinguishing effectiveness, discharge distance, expansion ratio and drain time. Demonstration testing also adhered to the standards outlined in NFPA.

3.4 Foam Quality Methods and Results

The field evaluations consisted of system checkout and foam quality. System checkout assured the function of the pump, turrets, handlines and pressures for each foam system. Foam quality evaluations included foam proportioning, fire extinguishing effectiveness, discharge distance, expansion ratio and drain time.

The measured foam concentration for the UHP turret was within tolerance ranges for one test at Dyess, all tests at MH and all tests at Tyndall. All foam concentration tests conducted at DM and Ellsworth were outside the tolerance ranges. Large variances in foam concentration were likely due to the plate and plunger system used to meter the foam. The foam proportioning system on the Tyndall vehicle was not functioning towards the end of fire testing and despite installing a new system, the foam was eventually premixed to the desired concentration in the water tank because the problem could not be resolved. Premixed Aqueous Film Forming Foam (AFFF) was used for all fire testing of the CAF and Hydrochem turret and handline.

Foam quality results for the CAF bumper turrets were all within requirements except for the drain time at Dyess. The foam concentration measurements for the CAF bumper turrets were within National Fire Protection Association (NFPA) tolerance ranges for one test at DM, one test at Ellsworth and three tests at MH. Due to foam proportioning malfunctions mentioned above, all other tests were outside the tolerance range and the measurements for Tyndall were especially high at 6.7% and 7.5%.

The foam expansion ratio and drain time for the Akron Brass UHP handline were all above the minimum requirements however, all the foam concentration measurements except two from DM were below the NFPA tolerance range. Foam proportioning was most difficult to control on the low flow 20 gpm UHP handline because of the way the plate and plunger system works by introducing foam through an orifice in the plate. While fluid calculations were done to determine the proper orifice size to obtain the correct foam proportion, metering at small flow rates is difficult to control with any degree of accuracy.

The expansion ratio and drain time results for the CAF handline exceeded the NFPA minimum requirements. MH and Ellsworth each had foam concentration measurements that fell within tolerance ranges while DM and Tyndall were both below the minimum range. While DM had the lowest foam concentration measurements, the foam expansion ratio and drain time were well above the minimum requirements.

3.5 Pump Cycle Methods and Results

AFRL was not provided with funds to complete time to failure analysis on the new centrifugal pump so pump cycle testing was determined to be the next best test method to stress the pump and test the reliability of the new technology. The Centrifugal Pump UHP P-19 (UHP P-19c) was operated using water only in an on/off cycle mode. Turning the pump completely on and off is one of the most mechanically stressful operating procedures. Hour and cycle counters were installed to obtain reliability data on all water and foam fire fighting systems. Five meters were installed, tracking operation of the UHP pump, UHP turret, UHP handline, CAF turret and CAF handline. Only data on the UHP pump and UHP turret are reported because the other systems were not used for pump cycle testing.

3.6 Three-Dimensional Engine Nacelle Fire Methods and Results

After the original test plan was written and approved, AFCESA requested Tyndall to complete a series of fire evaluations on the three-dimensional running fuel fire engine nacelle mockup. These tests evaluated effectiveness of low flow UHP handlines on hidden compartment running fuel fires and the ease of use for fighting these difficult fires. Testing was only conducted at Tyndall since AFRL is the only base that has this equipment. The 20 gpm UHP handline was able to successfully extinguish all three fires and was comparable to the performance of Halon 1211. The UHP P-19c handline extinguishment times ranged from 8.41 to 19.56 with an average of 13.13 seconds using 4.38 gallons (36.55 lbs) of agent.

3.7 Pool Fire Methods and Results

The application rates from the UHP P-19c field evaluations are shown in comparison to data obtained from the Fire Extinguishing Effectiveness Testing (FEET) completed at Tyndall in 2004 for the UHP, CAF and Hydro-Chem™ turrets systems. Handline comparisons were not conducted during FEET. All UHP P-19c testing was completed using the foam proportioning systems on the vehicles with the exception of the CAF and Hydro-Chem™ handline fires conducted at Tyndall because the foam proportioner did not function correctly. The purpose of the live fire evaluations was to show that even with minimal training and experience, firefighters can use UHP technology very effectively.

Forty-five fires were completed using the UHP bumper turret. UHP turret operations averaged 0.019 gallons per square foot (gsf) needed to extinguish the fire as compared to 0.014 gsf observed during the FEET study.

Eleven fires were completed using the CAF bumper turret. UHP P-19c CAF turret operations averaged 0.038 gsf as compared to 0.028 gsf observed during the FEET study.

Eleven fires were completed using the Hydro-Chem™ bumper turret. The UHP P-19c Hydro-Chem™ turret operations averaged 0.023 gsf as compared to 0.026 gsf observed during the FEET study.

Twenty-one fires were completed using the UHP handline. The FEET study did not evaluate handline operations, so no comparable data exists. Typically, application rates are improved by a factor of ten when compared to turret operations due to the firefighter having greater ability to control the application of the agent, resulting in less waste. The UHP handline average 0.0021 gsf application rate in comparison to 0.021 gsf for the UHP turret.

Fifteen fires were completed with the CAF handline with an average application rate of 0.0034 gsf (0.038 gsf for CAF turret).

Eighteen fires were completed with the Hydro-Chem™ handline with an average application rate of 0.0030 gsf (0.023 gsf for the Hydro-Chem™ turret).

3.8 Cold Weather Evaluations

Four fires using different fire fighting systems were completed by Ellsworth at temperatures near or below freezing with burning JP-8 on top of the frozen fire pit surface. The five vehicles used for this field evaluation were not modified with any additional cold weather protection for the new fire fighting system other than what already existed on the vehicle. Normal storage, maintenance and operational guidelines were followed for cold weather environments. While testing in sub-freezing temperatures was not required for the field evaluation, the results showed that the UHP P-19c was still effective at extinguishing fires using UHP and CAF plus dry chemical in the form of Hydro-Chem™. The handline fires were challenging for the firefighters as they had to extinguish the fires while walking on a sheet of ice. Review of the videos from each fire showed that the sub-freezing temperatures did not have any negative effects on agent stream characteristics or fire extinguishment effectiveness.

3.9 Design Issues Identified During Testing

During field evaluations, several engineering design issues were identified. While most issues were corrected either in the field or at the manufacturer, some issues were not resolved either because they were related to the P-19 and systems not related to the modified fire fighting package or they were issues that needed to be addressed by the component manufacturer. These issues included the air compressor (which was fixed), concurrent handline and turret operations (which was fixed), ability to use the handline and the vehicle to move at the same time, UHP handline heating up, UHP handline clogging, and a cooling system is required for pump gear box.

4.0 PHASE II; FIELD DEMONSTRATION OF FIVE MODIFIED P-19'S

4.1 Hardware Components

AFRL has maintained a partnership with several manufacturers over the development of the UHP technology, which has made the prototype vehicle a reality. The following sections give some details on three main components that were designed specifically for the UHP P-19c, but do not represent all the manufacturers who have worked with AFRL during the seven year development of UHP from 10 gpm to 300 gpm.

4.1.1 Darley Centrifugal Pump

W.S. Darley & Co designed, engineered, fabricated and tested a new six stage centrifugal pump capable of producing low and ultra high pressure with a single pump (Figure 4). The pump specifications for both low and ultra high pressure are shown in Table 1. The first stage provides low pressure while the other five stages build the pressure to UHP. Development started in 2006, and in 2007 Darley finalized a prototype for testing. The first unit was used for testing in the Oshkosh TD. Unfortunately, a problem with a snap ring caused the pump to fail but identified an issue that could easily be addressed in future units. Darley conducted additional testing on the next pump including hydrostatic pressure, high/low pressure performance points, endurance testing, dry run testing, wear component and calculated time to failure to assure reliability and durability. The notes from those tests are provided in Appendix A. Darley has finalized the commercial production of the pump and provided the first five units for retrofit for the field prototype testing.

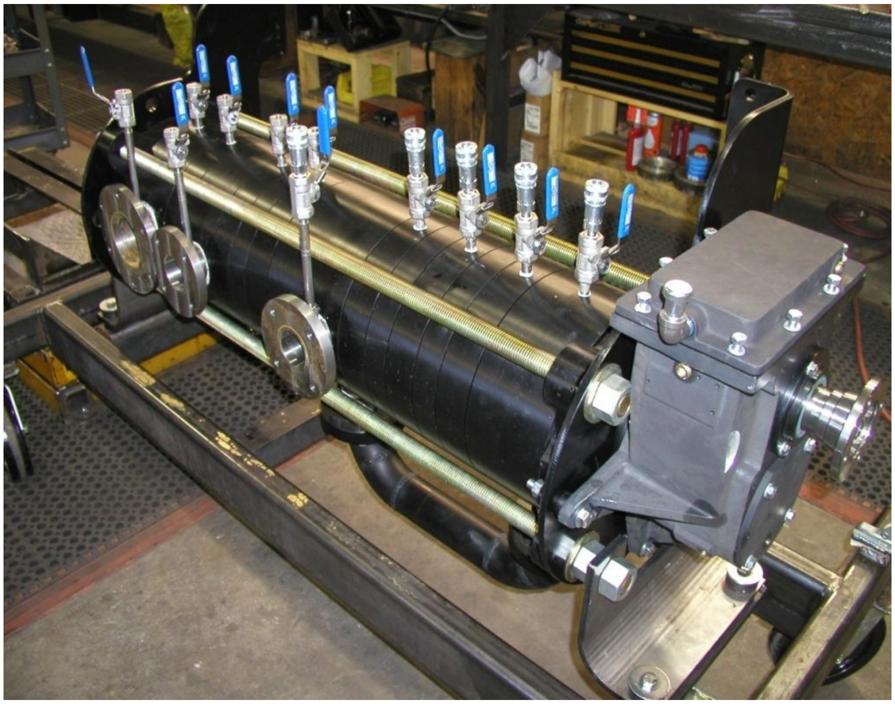


Figure 4. The Darley Six Stage Centrifugal Pump

Table 1. Performance Specifications for the Darley Six Stage Centrifugal Pump

	Pressure (psi)	Flow (gpm)	Power Requirements (hp)
Low Pressure	160	300	191.7
High Pressure	1300	300	375.9

4.1.2 Elkhart Brass Bumper Turret and Nozzles

Over the past several years, AFRL has been working with industry to develop an UHP high flow nozzle. AFRL has completed extensive research on fluid dynamics of UHP water and nozzle design to optimize flow, pressure, discharge distance and stream shape[7]. While several designs were fabricated and tested, AFRL could not obtain the performance necessary to scale UHP to large flow rates.

Elkhart Brass has engineered several UHP turret designs that have been tested on the UHP P-19p, Oshkosh TD and UHP P-19c. The most recent design incorporated a single waterway for both UHP and CAF foam Figure 5. The Elkhart Brass Combination UHP and Hydro-Chem™ Turret using a sliding plate that positions the selected nozzle in line with the turret waterway. This unique design allowed the turret to sit lower on the bumper, improving the field of view for the vehicle operator while simplifying the plumping and associated hardware. This system was installed on the Tyndall, MH and DM vehicles then later retrofitted on the Dyess and Ellsworth vehicles.

During testing at MH, an engineering defect was found with the UHP nozzle. The pattern selector sleeve broke away from the nozzle while cycling the nozzle from fog to straight stream. Elkhart Brass redesigned the part and performed cycle testing to assure performance. In total, four design modifications were required before the problem was completely resolved. Appendix B contains schematics and correspondence on the resolution to the failure. All five bases have new UHP nozzles with the current design changes incorporated and are functioning properly without any issues.

Figure 5. The Elkhart Brass Combination UHP and Hydro-Chem™ Turret

4.1.3 Akron Brass Bumper Turret and Nozzles

Akron Brass has designed and fabricated several versions of a UHP bumper turret and nozzle system. Originally, Akron Brass focused on the UHP nozzle and did not incorporate the Hydro-Chem™ nozzle. The first Akron Brass UHP turret and nozzle, tested on the UHP P-19p in 2006, was very effective and equaled performance to the Elkhart Brass UHP system in foam expansion ratio, drain time and discharge distance. The Akron Brass UHP nozzle had a different fog pattern than the Elkhart Brass nozzle and followed the traditional conical stream pattern (Figure 6). Also, due to the design of the nozzle, a small straight stream of water was discharged simultaneously from the center of the nozzle providing some level of longer range protection. The stream pattern was altered for the system used on the UHP P-19c.

Figure 6. Akron Brass UHP Nozzle in Fog Pattern

Fig. 7 shows the combination Akron Brass turret that was designed for the UHP P-19c. This system was originally installed on the Tyndall, Dyess and Ellsworth vehicles. Oshkosh was responsible for the design to marry the Hydro-Chem™ nozzle to the UHP nozzle so that both nozzles could be controlled with a single motor. Four issues were identified with this design and ultimately led to the replacement of the Akron Brass system with the Elkhart Brass system.

- The pressure at the nozzle would drop below 800 psi when in fog pattern, which would activate a warning that UHP pump pressure was below tolerance levels.

- The reaction force due to the placement of the Hydro-Chem™ nozzle would not allow the turret to move completely to the left while flowing foam or foam/dry chemical.

- The mounting of the Hydro-Chem™ nozzle obscured the field of view of the driver/operator, hindering extinguishment performance.

- Another design consideration of the bumper turret is the shape of the water stream in fog pattern. Akron Brass designed the pattern so that it formed a horizontal fan rather the traditional conical pattern. This was done to minimize overspray onto the windshield while improving the field of view of the driver/operator and still providing protection. Careful consideration needs to be made when reattaching or tightening the nozzle to assure the nozzle is in the right orientation otherwise the stream will not be horizontal, which reduces the effectiveness of the fog pattern.

Per the performance specifications in the contract, Oshkosh was notified of these problems and given the opportunity to either correct the Akron Brass system or replace the bumper turret with the Elkhart Brass system. Due to time and cost constraints, Oshkosh chose to replace the Akron Brass system with the Elkhart Brass system.

Figure 7. The Combination Akron Brass UHP and Hydro-Chem™ Turret

4.1.4 Oshkosh Truck Corporation

Oshkosh was responsible for the engineering design and modifications of the vehicle once the performance specifications were finalized by the Air Force. One of the main objectives of the modification was to minimize the complexity so that the firefighters could focus on fire fighting versus trying to learn new controls. While a few new switches were installed for added functions, such as CAF, the overall dashboard panel remained unchanged (Figure 8). Accomplishing the retrofit of the centrifugal pump system required Oshkosh to convert the original P-19 two dimensional line drawings into three dimensional solid models. The P-19 computer model allowed Oshkosh to design the vehicle in model space before the vehicle was physically modified. Creative engineering allowed for all the components to be fitted within the original envelope of the P-19 while maintaining the original 1000 gallon water capacity (previously the UHP P-19p water tank was cut to 750 gallons to accommodate the three plunger pumps and associated hardware). Oshkosh performed extensive testing to calibrate agent flow and pressure at each nozzle as well as testing each vehicle for stability (using tilt table testing) and weight distribution across each wheel (Appendix C).

Figure 8. UHP P-19c Cab Control Panel

4.1.5 HMA Fire Apparatus

HMA Fire Apparatus and AFRL have been working together on a variable speed joystick controller for the UHP and CAF turret (Figure 9). Current systems only allow the buyer to choose motors with a speed of either fast or slow. Fast motors can quickly overshoot the target while slow motors delay the reaction time of repositioning the turret. The solution was to design a variable speed controlled joystick. The farther the joystick is moved from the spring returned center, the faster the turret moves in the given direction, essentially creating a variable speed turret. The HMA joystick worked with both the Akron Brass and Elkhart Brass bumper turret systems.

Figure 9. HMA Force Feedback Joystick

4.2 UHP P-19c Demonstration Locations

Five Air Force bases were chosen based on their ability to conduct testing of the prototype vehicles using hydrocarbon fuel for live fire testing. The bases are located throughout the United States and offer a variety of environments, weather conditions and fire pit configurations. The effective burn areas for each fire pit are listed in **Error! Reference source not found.**. Figures 0-14 show the fire pits and mockups at each base participating in the UHP P-19c field evaluation.

Table 2. Effective Burn Areas

Location	Fire Pit Diameter (Ft)	Fire Pit Burn Area (Sq. Ft)
Davis-Monthan, Tucson, AZ (DM)	65	3318
Dyess, Abilene, TX (D)	100	7854
Ellsworth, Rapid City, SD (E)	100	7854
Mountain Home, Boise, ID (MH)	90	6362
Tyndall, Panama City, FL (T)	90	6362

Figure 10. Davis-Monthan Live Fire Burn Facility

Figure 11. Dyess Live Fire Burn Facility

Figure 12. Ellsworth Live Fire Burn Facility

Figure 13. Mountain Home Live Fire Burn Facility

Figure 14. Tyndall Live Fire Burn Facility

4.3 Training

AFRL provided training on each UHP P-19c vehicle upon delivery from Oshkosh. The firefighters who extinguished the fires were provided with classroom instruction and hands-on training from AFRL personnel with their vehicle to gain a level of comfort with the capabilities, limitations and differences in the vehicle versus a standard P-19. The classroom portion consisted of a PowerPoint presentation reviewing vehicle modifications; the different fire fighting systems; fire fighting operations; fire fighting techniques; special considerations related to the operation of the vehicle such as exercising caution around the UHP water streams; pumping limitations; videos of fires conducted by AFRL to show the optimal technique and a review of the requirements of the test plan. The classroom session lasted approximately two hours and was followed with hands-on training with the base's modified vehicle. The firefighters were given an overview of the modified fire fighting system and the components that needed to be maintained by the fire department, such as the oil level in the separator. The AFRL fire technician then completed a test run of the vehicle with the two firefighters involved in the testing. This allowed the firefighters to become familiar with the controls and the technique established by AFRL to provide the effective use of the UHP water and foam. AFRL assisted each base in performing the initial foam quality testing including foam expansion ratio, drain time, foam concentration and live fire testing. The hands-on portion of training required between 6-18 hours of time depending on the needs of the fire department.

Oshkosh provided training to the vehicle maintenance personnel upon delivery of the vehicle, including maintenance of the new fire fighting system, basic troubleshooting and repairs. The mechanical engineer responsible for the assembly of the UHP P-19c vehicles was sent to each base to provide this training. Oshkosh provided an overview of the major systems, how they functioned, maintenance items, the frequency of maintenance and contact information for the fire department and vehicle maintenance personnel in the event of a problem. Each base was provided with a supplemental technical order to describe the modifications to the vehicle. Training required one day with each base. AFRL established a three-tier system to address issues and problems with the modified vehicles. The base vehicle maintenance would coordinate with Oshkosh and AFRL initially. If the problem could not be resolved at the base, AFRL would provide specially trained vehicle maintenance personnel to assist in repairing the vehicle. If AFRL and the base vehicle department determined that the cost of repairs for labor and materials were in excess of $5000, Oshkosh would complete the repairs under warranty for a period of 12 months from vehicle delivery. AFRL will continue to provide advice to support issues related to the vehicles for the duration of their service life and assist the base vehicle maintenance with problems or repairs as necessary. As of the date of this report, no major repairs were required for any of the five vehicles.

4.4 UHP P-19c Field Demonstration Overview

The field demonstrations consisted of system checkout to assure the function of the pump, turrets, handlines and pressures for each foam system; and foam quality including foam proportioning, fire extinguishing effectiveness, discharge distance, expansion ratio and drain time. Demonstration testing also adhered to the standards outlined in NFPA 412 for the respective tests depicted in Table 3. The number of tests were based on the limited funding available for fuel and was designed to optimize the information needed by AFCESA to determine the viability of the new centrifugal pump. Testing was conducted using two firefighters. AFRL and AFCESA determined that having two firefighters with varying levels of experience would provide the best range of opinions and feedback. AFRL and AFCESA requested that one firefighter have a minimum of 10 years experience and one with less than 3 years of experience, if available. Limiting testing to two firefighters assured that a minimal level of proficiency was gained during testing while the difference in fire fighting experience provided two varying points of view from a seasoned versus rookie firefighter. The foam quality tests were requested to be conducted once at the vehicle delivery, once after the completion of the first 14 fires and once after all 28 fires were completed. The number of tests completed by each base varied from the original test plan. The fires were conducted in the order determined by the fire department.

Table 3. Field Evaluation Test Sequence

Test No.	No. of Trials	Method
1	3	300 GPM UHP turret: Measure foam concentration (NFPA 412 6.2.2); expansion ratio and drain time (NFPA 412 6.3); and discharge distance (NFPA 412 6.5)
2	3	20 GPM UHP handline: Measure foam concentration (NFPA 412 6.2.2); expansion ratio and drain time (NFPA 412 6.3); and discharge distance (NFPA 412 6.4)
3	3	300 GPM CAF turret: Measure foam concentration (NFPA 412 6.2.2).; expansion ratio and drain time (NFPA 412 6.3); and discharge distance (NFPA 412 6.5)
4	3	45 GPM UHP handline: Measure foam concentration (NFPA 412 6.2.2); expansion ratio and drain time (NFPA 412 6.3); and discharge distance (NFPA 412 6.4)
5	8	Conduct full pit fire using Akron Brass UHP turret (D, E, T)
6	8	Conduct full pit fire using Elkhart Brass UHP turret (MH, DM, T)
7	4	Conduct half pit fire using Akron Brass UHP handline (E, MH, DM)
8	4	Conduct half pit fire using Elkhart Brass UHP handline (E, T)
8	4	Conduct full pit fire using CAF turret (All)
9	4	Conduct half pit fire using CAF handline (All)
10	4	Conduct full pit fire using CAF turret with dry chemical (All)
11	4	Conduct half pit fire using CAF handline with dry chemical (All)
12	3	Conduct F100 running fuel fire using UHP handline (T)
13	5	Pump cycle testing: one minute run, one minute off (All)

DM = Davis-Monthan; D = Dyess; E = Ellsworth; MH = Mountain Home; T = Tyndall

4.5 Instrumentation and Equipment

Foam concentration was measured with a digital refractometer. Foam expansion ratio was measured with a digital scale. AFRL monitored the total number of starts and pump operation time for each of the five following modes: UHP turret, UHP handline, CAF turret, CAF handline and pump on. Pump on included all of the above plus idle time and cycles. Pump on was measured by installing a counter and an hour meter, similar to an odometer located in the cab. The intent was to have a source of this data without the operator needing to remember to take the measurements.

4.6 Foam Quality Methods and Results

Foam quality is one of the most important aspects of any fire fighting vehicle. If the foam quality is not properly maintained, the fire fighting performance can be reduced and the data obtained from testing cannot be consistently compared with other tests. Foam quality evaluations are also a critical tool to determine that the vehicle's fire fighting system is reliable. Changes in foam proportioning, or foam concentration, may indicate a maintenance issue with the foam proportioning system. As part of the test plan, each base was asked to check the foam quality at the beginning, middle and end of testing to assure that the fire fighting system was functioning as designed. All five bases conducted foam quality testing using the proportioning system specially designed to deliver 3% CAF handline/turret, 4% UHP turret and 6% UHP handline.

All five bases were provided with Chemguard military specification (MIL SPEC) aqueous film forming foam (AFFF) to reduce variations in fire fighting performance due to differences in foam effectiveness as extinguishment efficiencies can vary between manufacturers. However, due to some confusion about test requirements, Ellsworth used National Foam MIL SPEC AFFF. All MIL SPEC foams must meet minimum requirements as determined by MIL-F-24385F "Fire Extinguishing Agent, Aqueous Film Forming Foam (AFFF) Liquid Concentration, For Fresh and Sea Water" for foam quality and fire fighting capability[2]. The greatest difference in MIL SPEC foams when using a refractometer to measure concentration is the additive used to give the refractive index. The brix measurement is sensitive to the amount of refractive material and therefore, calibration curves and conversion factors were established for both foam brands.

Two different models of Atago digital refractometers were used during testing. The Pal-1 was purchased for Dyess, Ellsworth and Davis-Monthan because they did not possess a digital refractometer (Figure 15). Mountain Home and Tyndall used the PR-32, which both bases already had on hand (Figure 16).

Figure 15. Atago Pal-1 Digital Refractometer

Figure 16. Atago PR-32 Digital Refractometer

Both refractometers function alike and use the same calibration procedures, however; brix readings were shown by AFRL to vary between the models, therefore calibration curves not only had to be established for each brand of AFFF but also for the model of refractometer used by each base. This resulted in three different calibration curves (Appendix D). Both refractometers had a resolution of ±0.1 brix, which translates to ±0.4% foam concentration. For example, a brix reading of 0.9 could actually range anywhere from 0.85 to 0.94 with the refractometer rounding up to the nearest tenth of a brix. The resolution of the refractometer preferred by AFRL would be ±0.01 to provide better accuracy of the foam concentration since a small change in the brix can translate to a significant difference in the true foam concentration. Very few digital refractometers have this resolution and cost approximately $20,000, therefore, purchasing refractometers of this precision was not practical for this project. AFRL has no way to determine if discrepancies in foam concentration are from the foam proportioning system or the limited resolution of the refractometer. AFRL provided each base with a detailed set of instructions on calibration and use of the refractometer. Each base was given a class on how to use the equipment and take measurements to limit mistakes caused by different techniques. Foam concentration measurements were taken by using portions of solution drained the foam expansion and drain time testing. Refractive index readings of the test sample were converted to a percent foam concentration based on the equations calculated from the calibration curves. Each base was provided with a spreadsheet with the conversion factors already included so that the firefighters only had to enter the brix number from the refractometer to calculate foam concentration. The graphs of foam concentration measurement data for the UHP turret, UHP handline, CAF turret and CAF handline, which appear later in this section (Fig. 17 thru Fig. 20), show the foam concentrations converted from the brix readings along with the error associated with the resolution of the instrument. Dyess is represented by a diamond, Davis-Monthan by a square, Ellsworth by a triangle, Mountain Home by a circle and Tyndall by an asterisk.

Initial testing conducted at Tyndall on the first modified UHP P-19c included reevaluation of UHP foam at double the 3% concentration as was necessary at lower flow rates. Table 4 includes upper and lower limits on concentration for 4% and 5% AFFF mixtures. These limits were interpolated based on limits for 3% and 6% mixtures specified in NFPA 412.

Table 4. NFPA 412 and 414[8] Requirements for Foam Quality for Vehicles >528 to ≤1585 Gallons

Performance Description	NFPA Requirement
Handline Discharge Distance (NFPA 414)	65 feet
Bumper Turret Discharge Distance (NFPA 414)	150 feet
Expansion Ratio (Air aspirated foam)	5.0
Drain Time (Air aspirated foam)	3 minutes
Foam Concentration – 3%*	2.8 – 3.5 turret 2.8 – 4.0 handline
Foam Concentration – 4%**	3.7 – 4.7 turret 3.7 – 5.3 handline
Foam Concentration – 5%**	4.6 – 5.8 turret 4.6 – 6.6 handline
Foam Concentration – 6%*	5.5 – 7.0 turret 5.5 – 8.0 handline

*Based on NFPA 412 requirements.
**Based on interpolation between 3 and 6% from NFPA 412

Discharge distance, expansion ratio and drain time testing were all performed in accordance with NFPA 412[1] and 414[4]. Table 4 shows the minimum requirements defined by NFPA for foam quality. The handline and bumper turret discharge distance requirements are for systems that flow greater than 95 and 250 gpm, respectively. The expansion ratio and drain times requirements are for air aspirated foam since NFPA does not have a specific category for compressed air foam or UHP. NFPA 412 only gives foam proportioning ranges for 3 and 6%, therefore, the 4 and 5% range was interpolated.

NFPA 412 Handline Discharge Distance

1. Ground sweep nozzles and handline foam nozzles were discharged onto a hard surface for a period of 30 seconds.

2. Ground sweep nozzles were discharged from their fixed positions.

3. The tests were conducted under wind conditions of five mph or less.

4. Handline nozzles were held at their normal working height and tilted upward to form a 30-degree angle with the horizontal.

5. Immediately after foam discharge has stopped, markers were placed around the outside perimeter to preserve the identity of the foam pattern as it fell on the ground. For purposes of defining the edge of the pattern, any foam less than ½ inch in depth was

disregarded. The distance from the nozzle to the end of the effective foam pattern was measured and recorded on the data sheet.

6. Patterns from the straight stream were established, measured and recorded.

NFPA 412 Turret Discharge Distance

1. Discharge tests were conducted to establish the fire fighting foam discharge patterns produced and the maximum range attainable by the turret nozzle. The test was conducted under wind conditions of five mph or less. To determine maximum discharge range, the turret nozzle was tilted upward to form a 30-degree angle with the horizontal.

2. Foam was discharged onto a hard surface for a period of 30 seconds at the specified pressure, in both the straight stream and fully dispersed nozzle settings. Immediately after foam discharge was stopped, markers were placed around the outside perimeter to preserve the identity of the foam pattern as it fell on the ground. For purposes of defining the edge of the pattern, any foam less than ½ inch in depth was disregarded. The distance from the nozzle to the end of the effective foam pattern was measured and recorded on the data sheet.

Table 5 shows all the discharge distance data collected from the bases that completed the measurements. Unfortunately, not all the bases were able to complete the discharge distance testing requested by AFRL due to time constraints. Both the Elkhart Brass and Akron Brass UHP turret exceeded the NFPA minimum discharge distance. Initially, Dyess and Ellsworth were equipped with the Akron Brass bumper turret system while MH and DM were equipped with the Elkhart Brass bumper turret system. Tyndall was provided with both systems for comparison testing using the same vehicle. UHP turret discharge distance testing conducted by Tyndall showed that both systems performed similarly with the Akron Brass (224 feet) and the Elkhart Brass (220 feet) nozzles, exceeding both the NFPA 414 and P-19 technical order (TO 36A12-8-17-1[9]) requirements for bumper and roof turrets. This represents a 50% improvement over the bumper turret and 30% improvement over the roof turrets minimum requirements. The Hydro-Chem™ bumper turret nozzle used with both bumper turrets was identical and the only difference was the design used to mount the nozzle to the UHP turret system. Tyndall tested the Hydro-Chem™ turret in CAF mode while attached to the Elkhart Brass system. Results showed the nozzle could discharge 172 feet, which exceeded the minimum NPFA and P-19 TO requirements for bumper turrets (150 feet). The UHP and CAF handline discharge distance tests performed by Tyndall all exceeded the NFPA minimum requirements (65 feet); however, did not meet the minimum (96 feet) established in the P-19 TO for the 60 gpm handline nozzle. Turret testing completed by DM showed lower performance compared to Tyndall tests. Slight variations in wind and not orienting the vehicle such that the agent stream is discharged with the wind can have dramatic effects on discharge distance; therefore, all discharge distance testing at Tyndall was completed in low (less than two mph) wind conditions below the NFPA maximum of five mph. The other four bases were advised to follow these procedures as closely as possible but because wind conditions were not reported by the other bases, AFRL cannot make any conclusions about discrepancies in the data.

Table 5. Discharge Distance Data Summary for UHP and CAF Systems

	UHP Turret (ft)	CAF Turret (ft)	UHP Handline (ft)	CAF Handline (ft)
DM	184 (E)	121*	63 (A)*	79
DM	190 (E)	135*	61 (A)*	63
MH	232 (E)		55 (A)*	
Tyndall	220 (E)	172	67 (E)	67
Tyndall	224 (A)		65 (A)	
Tyndall			67 (A)	
Standard P-19	500 gpm Roof Turret (ft)	250 gpm Bumper Turret (ft)	60 gpm Handline (ft)	
P-19 Technical Order Specifications	175	150	96	

* Did not meet minimum NFPA requirements for bumper turrets or handlines.
A = Akron Brass nozzle; E = Elkhart Brass nozzle.

NFPA 412 Expansion Ratio and Drain Time

The foam sample was collected in a standard 1000-mL-capacity graduated cylinder. The cylinder was cut off at the 1000-mL mark to ensure a fixed volume of foam as a sample. The cylinder was marked in 10-mL graduations below the 100-mL mark.

The empty weight of the foam sample container was recorded to the nearest gram on a balance having a maximum capacity sufficient to weigh the foam sample container and the foam sample. The foam sample collector was then located in the center of the discharge pattern. The foam sample container was positioned at the bottom of the foam collector so that the foam hitting the collector flowed into the container. The foam nozzle was aimed so that the foam deflects off the side of the foam collector, adjusted to its normal operating pressure, and then moved so as to discharge foam onto the foam sample collector. As soon as the foam sample container was completely filled with foam, the discharge nozzle was shut off and the timing of the 25 percent drainage started.

The foam sample container was removed from the base of the foam collector, excess foam struck off the top of the foam container using a straight edge and any remaining foam wiped from the outside surface of the container. The container was then placed on the balance. The total weight of the foam sample and container was determined to the nearest gram. The weight of the foam sample in the container was determined by subtracting the weight of the empty container from the weight of the container filled with the foam. The weight of the foam sample in grams was divided by 4 to obtain the equivalent 25 percent drainage volume in milliliters.

The foam sample container was placed on a level surface at a convenient height. At 30-second intervals, the level of accumulated solution in the bottom of the cylinder was noted and recorded. The drainage time versus the volume relationship was recorded until the 25 percent volume was exceeded. The 25 percent drainage time was then interpolated from the data.

Foam samples were weighed to the nearest gram. The expansion of the foam was calculated in Equation 1:

$$\text{Expansion} = \frac{1000 \text{ liquid (gr)}}{\text{full weight (gr)} - \text{empty weight (gr)}} \qquad (1)$$

Where:
Full weight is the weight of the cylinder plus the weight of the foam.
Empty weight is the weight of the cylinder when dry.

Table 6 shows all the foam quality data collected for both the Elkhart Brass and Akron Brass UHP bumper turrets. All the numbers with an asterisk were outside the NFPA 412 and 414 requirements. The expansion ratio measurements were within NPFA requirements for all tests except DM and Ellsworth. Possible explanations include the method used to collect the foam, not completely cleaning the excess foam off the cylinder prior to weighing, debris in the cylinder or low foam concentration due to the foam proportioner not functioning correctly. Drain times exceeded the minimum requirements for all tests. Not all requested expansion ratio and drain time tests were completed due to time constraints.

Table 6. Foam Quality Data for the Elkhart Brass and Akron Brass UHP Bumper Turrets				
	Ultra High Pressure Turret			
	Exp Ratio (1)	**Exp Ratio (2)**	**Drain Time (1)**	**Drain Time (2)**
DM (E)				
1	*3.82**	*3.88**	5.45	5.43
2	*3.74**	*3.49**	>6	5.40
Dyess (A)				
1	5.11	5.26	4.57	4.54
2	5.75	5.42	3.54	4.06
Ellsworth (A)				
1	*4.10**	*4.18**	>6	>6
MH (E)				
1	6.05	5.80	>6	>6
2	5.78	5.75	>6	>6
Tyndall				
1 - Elkhart Brass (4)	6.68	7.08	4.23	4.15
2 - Akron Brass (6)	9.95	10.20	6.00	5.40
3 - Akron Brass (5)	9.80	9.70	6.00	6.08
4 - Akron Brass (4)	7.35	7.03	6.11	6.13

* Did not meet minimum NFPA requirements
(A) = Akron Brass nozzle and turret; (E) = Elkhart Brass nozzle and turret
(4) = 4% foam concentration; (5) = 5% foam concentration; (6) = 6% foam concentration

The measured foam concentration was within tolerance ranges for one test at Dyess, all tests at MH and all tests at Tyndall (Fig. 18). All foam proportioning tests conducted at DM and Ellsworth were outside the tolerance ranges. Large variances in foam concentration were likely due to the plate and plunger system used to meter the foam. While each system was fully tested at Oshkosh for proper performance, they are still subject to operational problems, which can affect foam concentration measurements. The foam proportioning system on the Tyndall vehicle was not functioning towards the end of fire testing and, despite installing a new proportioning system, the foam was eventually premixed in the water tank because the problem could not be resolved. Premixed AFFF was used for fire testing of the CAF and Hydro-Chem™ turret and handline.

Tyndall also conducted a series of tests to look at foam quality as a function of foam concentration (Figure 17). When UHP was first introduced in the FRE fire fighting system, 6% foam (double the amount of Type 3) was used to provide additional burnback protection due to the small amount of foam and water needed to extinguish the fire. As UHP technology scaled from 14 gpm to 300 gpm, AFRL felt that reevaluating the necessity to continue the use of enriched foam was appropriate. Additional foam expansion ratio and drain time tests were conducted at 6%, 5% and 4% foam concentration to determine if the foam concentration could be reduced while meeting NFPA standards and while maintaining fire fighting performance. Results showed that 4% foam of Type 3 AFFF used with the UHP turret exceeded the NFPA minimum requirements for expansion ratio and drain time and provided effective extinguishment and burnback protection. The use of foam at 5% and 6% did not improve foam quality and just resulted in excess agent that was not necessary to maintain optimal performance. The foam proportioning system was set to 4% for the UHP turret on all 5 trucks as a result of the foam concentration test results. The final 4% foam concentration was tested on a half pit hydrocarbon fuel fire at Tyndall to assure that extinguishment and burnback properties were not affected by the reduction in foam or changes to the foam blanket. The 4% foam concentration provided effective extinguishment and burnback protection.

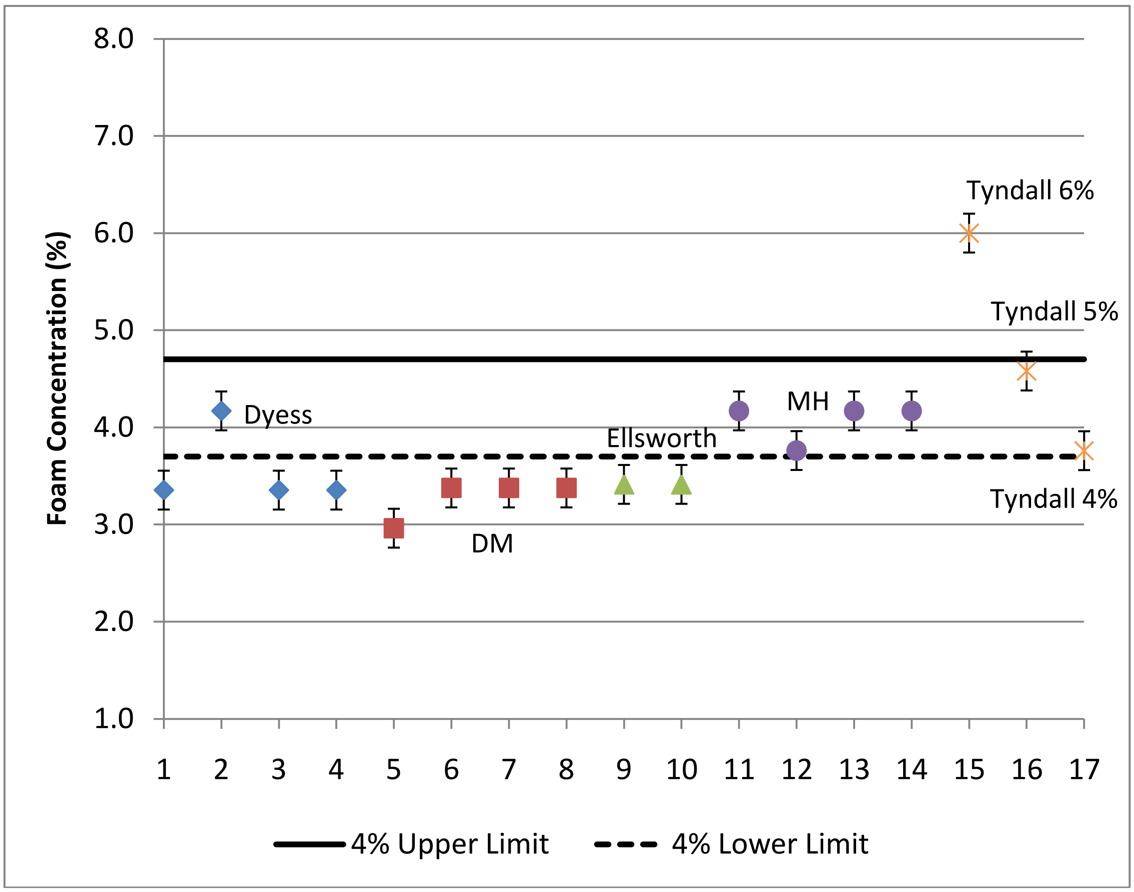


Figure 17. Foam Concentration Measurements for the UHP Turret

Foam quality results for the CAF bumper turrets were all within requirements except for the drain time at Dyess (Table 7). AFRL representatives were present when the test was conducted and everything was done according to procedure. Since the expansion ratio and foam concentration were well above minimum requirements, the drain time should have easily exceeded six minutes, as in tests conducted by other bases. No explanation for this anomaly can be provided.

Table 7. Foam Quality Data for the Compressed Air Foam Bumper Turret

	Compressed Air Foam Bumper Turret			
	Exp Ratio (1)	**Exp Ratio (2)**	**Drain Time (1)**	**Drain Time (2)**
DM				
1	6.68	6.68	>6	>6
2	7.05	5.92	>6	>6
Dyess				
1	7.41	7.20	<2.5*	<2.5*
Ellsworth				
1	6.95	6.86	>6	>6
MH				
1	7.41	7.71	>6	>6
2	6.73	6.84	>6	>6
Tyndall				
1	8.70	9.10	5.45	5.30

* Did not meet minimum NFPA requirements

The foam concentration measurements for the CAF bumper turrets were within NFPA tolerance ranges for one test at DM, one test at Ellsworth and three tests at MH (Figure 18). All other tests were outside the tolerance range and the measurements for Tyndall were especially high at 6.7% and 7.5%. When live fire tests of the CAF system (see Section 4.6) on the Tyndall vehicle, were conducted late in 2008, foam was premixed because the foam proportioner was not functioning. Foam concentration testing was not repeated.

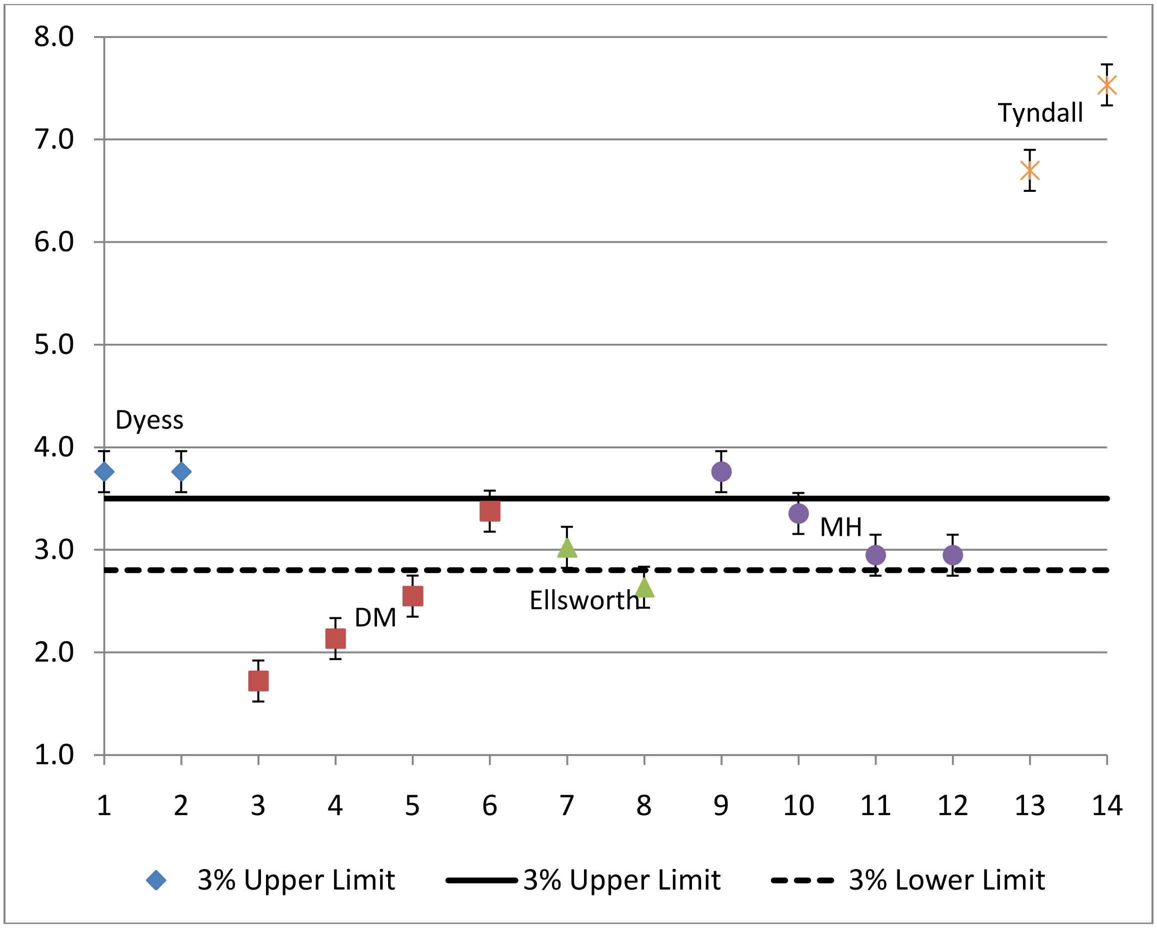


Figure 18. Foam Concentration Measurements for the CAF Turret

Table 8 shows that the foam expansion ratio and drain time for the Akron Brass UHP handline were all above the minimum requirements however, all the foam concentration measurements except two from DM were below the NFPA tolerance range (Figure 19). Foam proportioning was most difficult to control on the low flow 20 gpm UHP handline. The plate and plunger system works by introducing foam through an orifice in the plate. While fluid calculations were done to determine the proper orifice size to obtain the correct foam proportion, metering at small flow rates is difficult to control with any degree of accuracy.

Table 8. Foam Quality Data for the Akron Brass UHP Handline

	Ultra High Pressure Handline			
	Exp Ratio (1)	**Exp Ratio (2)**	**Drain Time (1)**	**Drain Time (2)**
DM				
1	6.70	7.16	5.17	4.41
2	5.88	5.82	5.15	4.41
Ellsworth				
1	5.88	6.43	*	*
MH				
1	8.70	8.42	>6	>6
2	7.51	7.78	5.04	4.40
Tyndall				
1	7.63	8.90	>5.3	>5

* Information not provided by the base.

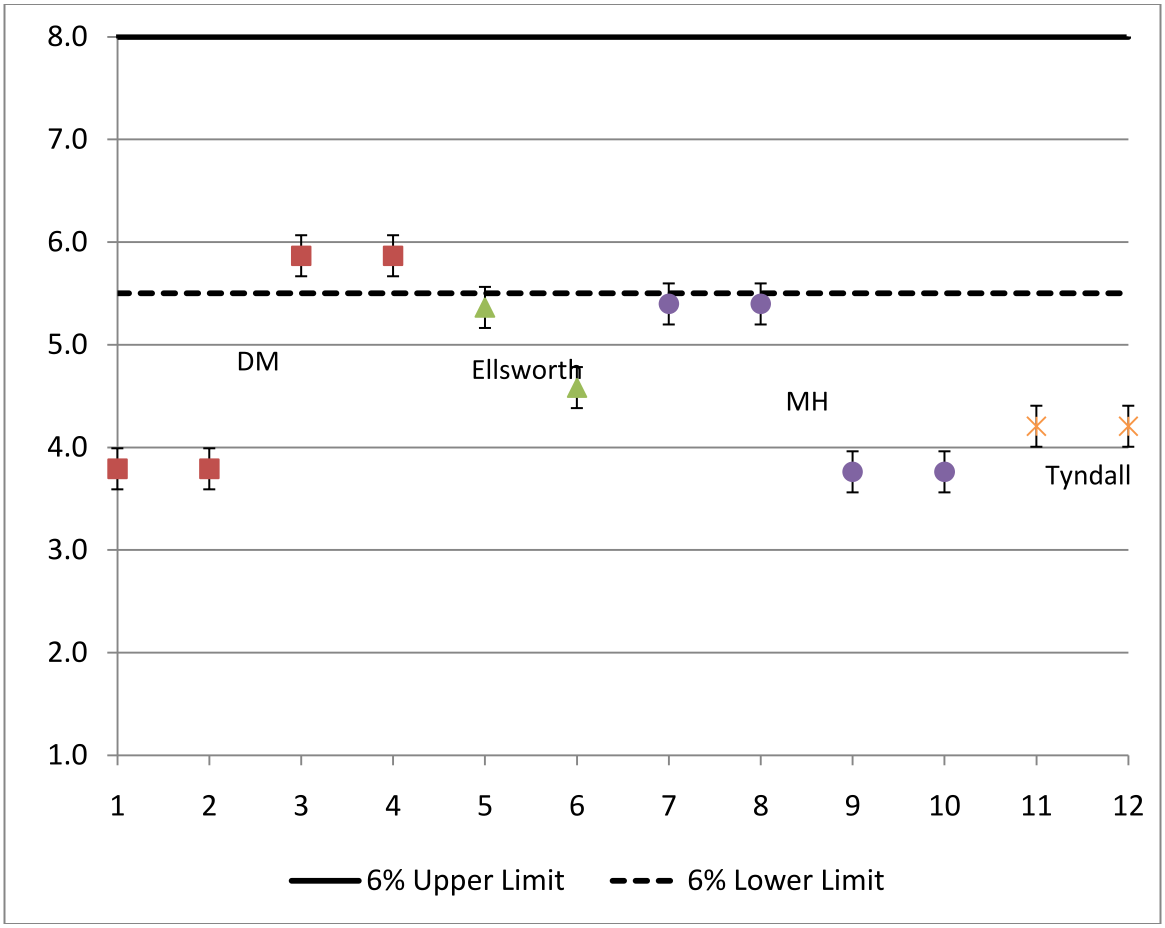


Figure 19. Foam Concentration Measurements for the UHP Handline

The expansion ratio and drain time results for the CAF handline all exceeded the NFPA minimum requirements (Table 9). As seen in the CAF turret testing, the foam concentration for the handline showed similar results (Fig. 20). MH and Ellsworth both had foam proportioning measurements that fell within tolerance ranges while DM and Tyndall were both below the minimum range. While DM had the lowest foam concentration measurements, the foam expansion ratio and drain time were all well above the minimum requirements. AFRL was present during the first measurement (a second test was performed a week later with similar results) and the discrepancy in expansion ratio and drain time as a function of foam concentration cannot be explained.

Table 9. Foam Quality Data for the Compressed Air Foam Handline

	Compressed Air Foam Handline			
	Exp Ratio (1)	Exp Ratio (2)	Drain Time (1)	Drain Time (2)
DM				
1	9.00	8.63	>6	>6
2	7.59	6.59	>6	5.36
Ellsworth				
1	5.78	5.83	>6	>6
MH				
1	10.10	10.00	>6	>6
2	11.24	11.14	>6	>6
Tyndall				
1	7.48	8.11	>5	>5

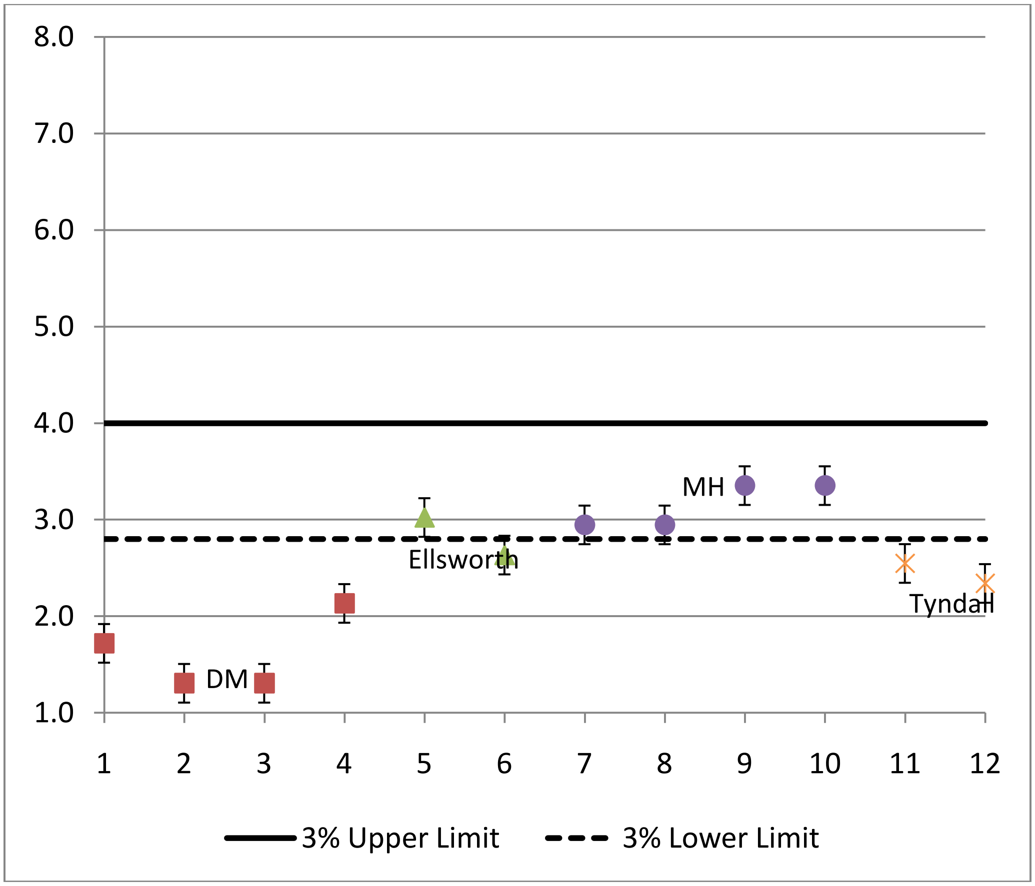


Figure 20. Foam Concentration Measurements for the CAF Handline

4.7 Pump Cycle Methods and Results

AFRL was not provided with funds to complete time to failure analysis on the new centrifugal pump so pump cycle testing was determined to be the next best test method to stress the pump and test the reliability of the new technology. The UHP P-19c was operated using water only in an on/off cycle mode. Turning the pump completely on and completely off is one of the most mechanically stressful operating procedures. Hour and cycle counters were installed to obtain reliability data on all water and foam fire fighting systems. Five meters were installed, tracking operation of the UHP pump, UHP turret, UHP handline, CAF turret and CAF handline. Only data on the UHP pump and UHP turret are reported because the other systems were not used for pump cycle testing. This monitoring will continue as the vehicles are used by the fire departments and will also allow AFRL to identify the pump run time in the event of a problem or failure.

Each base was requested to conduct pump cycle testing five times during the test period totaling at least five hours of cycle testing. Below are the procedures for completing the test:

1. Check the fuel level in the UHP P-19c.

2. Park the truck near the hydrant. Connect the hydrant to the truck using a 2.5 inch hose. Turn the water on and fill the water tank. Leave the hydrant on.

3. Record the time and cycle count from the water pump and high pressure turret counters.

4. Select high pressure. Do not select foam. Start the water pump. Open the discharge valve. Pump water for approximately one minute.

5. Close the discharge valve. Turn the pump off. Wait for approximately one minute.

6. Repeat steps 4 and 5 until 30 cycles are completed (one hour).

7. When finished, record time and cycle data.

Table 10 shows a summary of the dates, times and cycles completed for each base. DM and MH completed the minimum requested five hours of testing while Tyndall completed six hours of testing. Dyess completed two hours of cycle testing and Ellsworth was not able to complete any cycle testing. Even though Dyess only completed two hours of pump cycle testing, the vehicle had over 18 hours of discharge time on the pump and 685 cycles. The majority of the pump discharge time was completed by Oshkosh during modification of the vehicle to test various components of the UHP system. All five pumps performed well and no problems were identified during testing, assuring that the issue with the snap ring that caused the failure of the Oshkosh TD was resolved by Darley.

Table 10. Pump Cycle Testing Summary

UHP Pump Cycle Testing									
Davis-Monthan AFB, AZ									
Date	**Run Time**	**Water Pump**				**UHP Turret**			
		Time (Hrs)		**Cycles**		**Time (Hrs)**		**Cycles**	
		Start	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
11/5/2008	60	8.48	8.92	276	301	1.04	1.42	141	165
11/5/2008	60	8.93	9.31	302	338	1.43	1.66	166	195
11/6/2008	30	9.81	10.05	405	418	1.79	2.00	230	242
11/13/2008	60	10.96	11.51	494	530	2.31	2.78	303	330
12/4/2008	60	11.84	12.43	563	592	2.81	3.34	337	366
12/5/2008	30	12.64	12.9	606	623	3.46	3.64	376	393
Dyess AFB, TX									
Date	**Run Time**	**Water Pump**				**UHP Turret**			
		Time (Hrs)		**Cycles**		**Time (Hrs)**		**Cycles**	
		Start	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
11/3/2008	60	16.55	17.05	597	627	3.71	4.19	487	517
11/5/2008	60	17.67	18.17	655	685	4.37	4.85	565	595
Ellsworth AFB, SD									
Date	**Run Time**	**Water Pump**				**UHP Turret**			
		Time (Hrs)		**Cycles**		**Time (Hrs)**		**Cycles**	
		Start	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
Final	na	na	3.91	na	205	na	2.98	na	456
Mountain Home AFB, ID									
Date	**Run Time**	**Water Pump**				**UHP Turret**			
		Time (Hrs)		**Cycles**		**Time (Hrs)**		**Cycles**	
		Start	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
10/5/2008	60	8.89	9.60	423	455	1.88	2.30	260	294
10/21/2008	60	10.39	11.1	483	513	2.8	3.28	340	372
10/23/2008	60	11.39	11.9	530	561	3.34	3.82	385	416
11/5/2008	60	11.98	12.48	570	600	3.87	4.37	430	460
11/13/2008	60	12.55	13.07	608	639	4.38	4.70	471	503
Tyndall AFB, FL									
Date	**Run Time**	**Water Pump**				**UHP Turret**			
		Time (Hrs)		**Cycles**		**Time (Hrs)**		**Cycles**	
		Start	**End**	**Start**	**End**	**Start**	**End**	**Start**	**End**
6/26/2008	60	6.54	na	202	na	1.03	na	224	na
na	60	na	na	na	na	na	na	na	na
na	60	na	na	na	na	na	na	na	na
7/22/2008	60	9.90	10.40	312	342	2.61	3.09	378	409
10/3/2008	60	13.08	13.58	516	546	4.21	4.69	546	579
10/21/2008	60	13.68	14.19	554	615	4.74	5.14	584	646

na = The pump cycle testing was completed however the operator did not document the date, times or pump cycles.

4.8 Three-Dimensional Engine Nacelle Fire Methods and Results

After the original test plan was written and approved, AFCESA requested Tyndall to complete a series of fires on the three-dimensional running fuel fire engine nacelle mockup. These tests evaluated effectiveness of low flow UHP handlines on hidden compartment running fuel fires and the ease of use for fighting these difficult fires. Testing was only conducted at Tyndall since AFRL is the only base that has this equipment. Three running fuel fires were extinguished using the 20 gpm UHP handline on the F100 engine nacelle test fixture to determine the effectiveness of UHP foam and water on three dimensional spray fuel fires. Figure 21 shows the layout of the nozzles and baffles inside the fixture. Previous testing with other UHP handline systems has shown this technology to be highly effective on this type of fire and that it can meet or exceed the 30 second maximum extinguishment time for flightline fire extinguishers.[10,11]

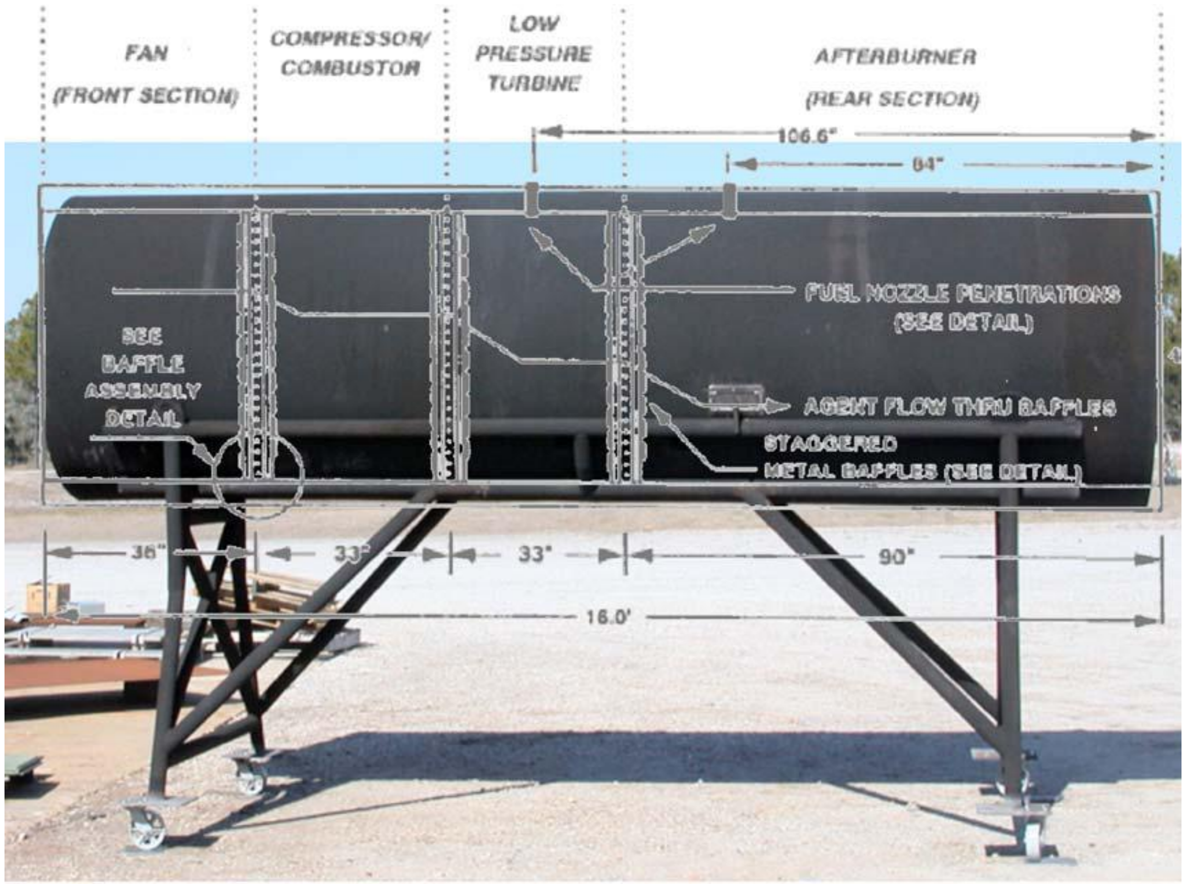


Figure 21. Diagram of the F100 Engine Nacelle[10]

The fires were conducted as follows:

Initial Fire

- Ignite afterburner (nozzle 3) fuel spray (JP-8, 2 gpm)
- Heat tail pipe for five minutes
- Shut off fuel
- Allow metal to cool to 475 ± 25°F
- Flow 25 gallons of JP-8 through the fixture into the concrete pan
- Ignite low pressure turbine and afterburner fuel sprays with a suitable torch applied through the ignition port
- Ignite pan
- Allow to burn for 15 seconds
- Extinguish fire with UHP handline using water and 6% AFFF
- Record time to extinguish

Subsequent Fires

- Initial heating of tail pipe is not necessary if all three fires are conducted back to back
- Flow 25 gallons of JP-8 through the fixture into the concrete pan
- Ignite low pressure turbine and afterburner fuel sprays with a suitable torch applied through the ignition port
- Ignite pan
- Allow to burn for 15 seconds
- Extinguish fire with UHP handline using water and 6% AFFF
- Record time to extinguish

The 20 gpm Akron Brass UHP handline was able to successfully extinguish all three fires and was comparable to the performance of Halon 1211. The UHP P-19c handline extinguishment times ranged from 8.41 to 19.56 with an average of 13.13 seconds using 4.38 gallons (36.55 lbs) of agent (Table 11). In comparison, Halon 1211 averaged 14.18 seconds using 67.6 lbs of agent.[12]

Table 11. F100 Engine Nacelle Extinguishment Times for Akron Brass UHP Handline

Test Number	Extinguishment Time (seconds)
1	19.56
2	8.41
3	11.41

4.9 Pool Fire Methods and Results

Live fire evaluations were conducted at all five bases to show the ease of use of the system outside the laboratory atmosphere. All half and full pit pool fires were conducted using the following procedures:

The water level was adjusted in the pit such that the gravel was covered with water as exposed gravel can skew the extinguishment results by providing a three dimensional aspect to the fire as well as a heat sink. Small residual fires in the gravel surrounding the outside of the pit or the berm dividing the pit were not counted as part of the total extinguishment time as these fires can require a lot of time to extinguish skewing the times in comparison to the suppression of the primary fire. The videos from all the fires were reviewed by AFRL to assure consistency in determining when the fire was extinguished.

1. AFRL requested that all tests be conducted when the wind was less than 15 mph as determined by a wind meter, however, some bases could not meet this requirement because of naturally windy environments. Testing was not limited based on temperature or humidity. Wind was from any direction.

2. A pretest briefing was conducted. Test objectives and personnel assignments were identified. The test director verified that all personnel were familiar with emergency procedures.

3. Video cameras were placed according to wind direction. Prior to each test, test information was recorded on each video camera and an accompanying data sheet was prepared. Information recorded included test number, date, test type and fire size.

4. All equipment was verified operational and fully serviced, including the test article, backup truck, torch and camera(s).

5. All non-essential personnel were moved to a safe location and all personnel involved in testing were in their assigned stations prior to approval for beginning testing (as signaled by the test operator). The test article and the backup truck were placed in the appropriate locations, considering the wind direction and fuel lighting approach.

6. Steps 1-5 were completed prior to pumping fuel. Fuel was pumped into the fire pit. All half pit fires used up to 250 gallons of fuel and full pit fires used up to 500 gallons of fuel.

7. The safety officer verified that all personnel were ready for testing. The cameras were started and the fuel was ignited.

8. Once the fuel was fully involved, extinguishment started. AFRL has no requirement for a set pre-burn time, however sufficient time was allowed to have full fuel involvement prior to extinguishment. The vehicle was advanced at the discretion of the vehicle firefighter. During UHP testing, only UHP foam and water were used to extinguish the fire. During CAF, only compressed air foam and water were used to extinguish the fire. During CAF

with dry chemical, compressed air foam, water and dry chemical will be used simultaneously for the duration of extinguishment.

9. Data and video recording were discontinued and the data sheet was completed.

10. The fire pit area was cleaned and the vehicle was reserviced.

Table 12 shows the total number of fires outlined in the test plan versus the actual number of fires completed. Some fires were not completed due to weather, equipment problems and repairs to fire pits. In particular, the CAF and Hydro-Chem™, which used CAF, were not completed or only partially completed by Ellsworth and Dyess due to reaction force problems with the Akron Brass turret, as mentioned in Section 4.1.3. The data is separated by the agent application used. Specific observations for each fire as reviewed by AFRL can be found in Appendix E. The extinguishment times used to calculate efficiency were based on AFRL review of each video so that determination of "fire out" was consistent. In addition, time to reposition the vehicle (while no foam was being discharged) was not included in the extinguishment efficiency measurements. The notes in Appendix F state the total time to extinguish along with the length of agent application.

Table 12. Total Number of Fires Requested and Completed on the UHP P-19c

Test Type	Test Requested	Tests Completed
UHP Turret	48	45
CAF Turret	20	11
Hydro-Chem™ Turret	20	11
UHP Handline	20	21
CAF Handline	20	15
Hydro-Chem™ Handline	20	18

The Fire Extinguishing Effectiveness Testing[6] (FEET) study established application rate as the unit of measure to compare different flow rates and application technologies on an equal basis. Application rate is defined as the quantity of agent applied divided by the area of fire extinguished (gallons/sq ft). For these tests of the P-19c, the total quantity of agent applied was determined by multiplying nominal flow rate of the system (Table 13) by the total time agent was flowed. The flow rate of each system on each vehicle was verified by Oshkosh and not by each base, therefore, the flows for each fire fighting system were assumed to be accurate. The area of the fire extinguished used to calculate application rate for these tests was estimated by visually studying the videos of testing submitted to AFRL. Effective fire area was then estimated using the fire pit area multiplied by the estimated fire size in percent.

Table 13. Nominal Foam Solution Flow Rates

Test Type	Nominal Flow Rate (gpm)
UHP Turret	300
CAF Turret	300
Hydro-Chem™ Turret	300
UHP Handline	20
CAF Handline	45
Hydro-Chem™ Handline	45

Table 14 shows the average application rate for each turret system for the UHP P-19c as compared to results obtained in FEET. Overall, all three technologies were more efficient than low pressure foam application typical of the standard P-19, with UHP showing the greatest level of improvement.

Table 14. Summary of Application Rates of Turret Systems

	FEET (gal/sq ft)	UHP P-19c (gal/sq ft)
UHP Turret	0.014	0.020
CAF Turret	0.028	0.038
Hydro-Chem™ Turret	0.027	0.023
Standard P-19 Low Pressure Turret	0.044	na

Statistical comparisons of performance between the UHP-P19c fire fighting systems with the standard P-19 system are provided in the first six lines of Table 15. These comparisons were accomplished using the ”t” test, showing confidence levels that data sets are statistically different from each other. For each comparison, Test 1 represents the system with the lower mean application rate and Test 2 represents the system with the higher mean application rate. All systems except the CAF turret exceeded the standard P-19 system performance demonstrated in FEET to a very high confidence (≥ 99%). The CAF turret also exceeded the standard P-19 performance but only to an 88% level of confidence.

Performance comparisons between the UHP P-19c UHP turret, CAF turret and Hydro-Chem™ turret with corresponding systems tested during FEET are provided in the last 3 lines of Table 15. The UHP turret and CAF turret performance during FEET exceeded the performance of the UHP P-19c to a confidence level ≥ 98% for both systems. The 76% confidence level comparing the UHP P-19c Hydro-Chem™ turret performance to that observed during FEET is not adequate to accept that the UHP P-19c performance is better than the FEET systems performance.

Table 15. Statistical Comparisons of UHP-P19c Agent Application Rates with FEET Results

Test 1				Test 2				Combined		
	Mean	Std Dev	n		Mean	Std Dev	n	DOF	Std Dev	Probability
UHP P-19c UHP turret	0.019	0.011	45	FEET P-19	0.044	0.012	22	65	0.011	>.99
UHP P-19c CAF turret	0.038	0.019	11	FEET P-19	0.044	0.012	22	31	0.015	0.88
UHP P-19c Hydro-Chem™ turret	0.023	0.016	11	FEET P-19	0.044	0.012	22	31	0.014	0.99
UHP P-19c UHP handline	0.0021	0.0016	21	FEET P-19	0.044	0.012	22	41	0.0086	>.99
UHP P-19c CAF handline	0.0034	0.0019	15	FEET P-19	0.044	0.012	22	35	0.0092	>.99
UHP P-19c Hydro-Chem™ handline	0.0030	0.0027	18	FEET P-19	0.044	0.012	22	38	0.0090	>.99
FEET UHP turret	0.014	0.0024	20	UHP P-19c UHP turret	0.021	0.011	38	56	0.0092	0.99
FEET CAF turret	0.028	0.0049	26	UHP P-19c CAF turret	0.038	0.019	11	35	0.011	0.98
UHP P-19c Hydro-Chem™ turret	0.023	0.659	11	FEET Hydro-Chem™ turret	0.026	0.0079	25	34	0.011	0.76

The FEET tests were conducted using a limited group of experienced firefighters, tightly controlled application methods and a limited range of weather conditions. The tests were conducted at Tyndall with wind less than 7 mph with temperature ranging from the low 40's to mid 90's °F. Higher wind (>30 mph) and lower temperatures (<32°F) were experienced at Ellsworth and MH during UHP P-19c testing. These tests are important to include because they show that the ability of the UHP P-19c to extinguish fires is not limited to low wind and moderate temperatures. The vehicles were not equipped with any additional winterization equipment for the new fire fighting system and the vehicle was maintained and operated the same as the standard P-19. The FEET study was conducted in a pit without a steel aircraft mockup while each base participating in the field evaluations had a different size and style of mockup. All tests were conducted from a stationary position, rather than moving the truck as the fire was extinguished. The FEET tests were conducted at lower flow rates of 70-100 gpm compared to 300 gpm for the UHP P-19c. Higher flow on the UHP P-19c offered greater advantage by providing greater discharge distance. The CAF and Hydro- Chem™ tests during FEET were nominally tested at 125-220 gpm, so the difference in discharge distance was not as great for these technologies.

The application rates from the UHP P-19c field evaluations are shown in comparison to data obtained from FEET for the UHP, CAF and Hydro-Chem™ turrets. Handline comparisons were not completed during FEET. All testing was completed using the foam proportioning systems on the vehicles with the exception of the CAF and Hydro-Chem™ handline fires conducted at Tyndall because the foam proportioner was not functioning correctly. The purpose of the live fire evaluations was to show that even with minimal training and experience, UHP technology is still very effective even with a less experienced firefighter.

Forty-five fires were completed using the UHP bumper turret (Figure 22). UHP turret operations averaged 0.019 gallons per square foot (gsf) as compared to 0.014 gsf observed during the FEET study. One fire from Dyess took 91 seconds to extinguish because the vehicle was repositioned three times during extinguishment, which extended fire fighting time. The DM fires were all extinguished quickly and with minimal agent because the fires were small and did not involve the entire fire pit area, averaging between 11 to 26 seconds, without having to reposition the vehicle.

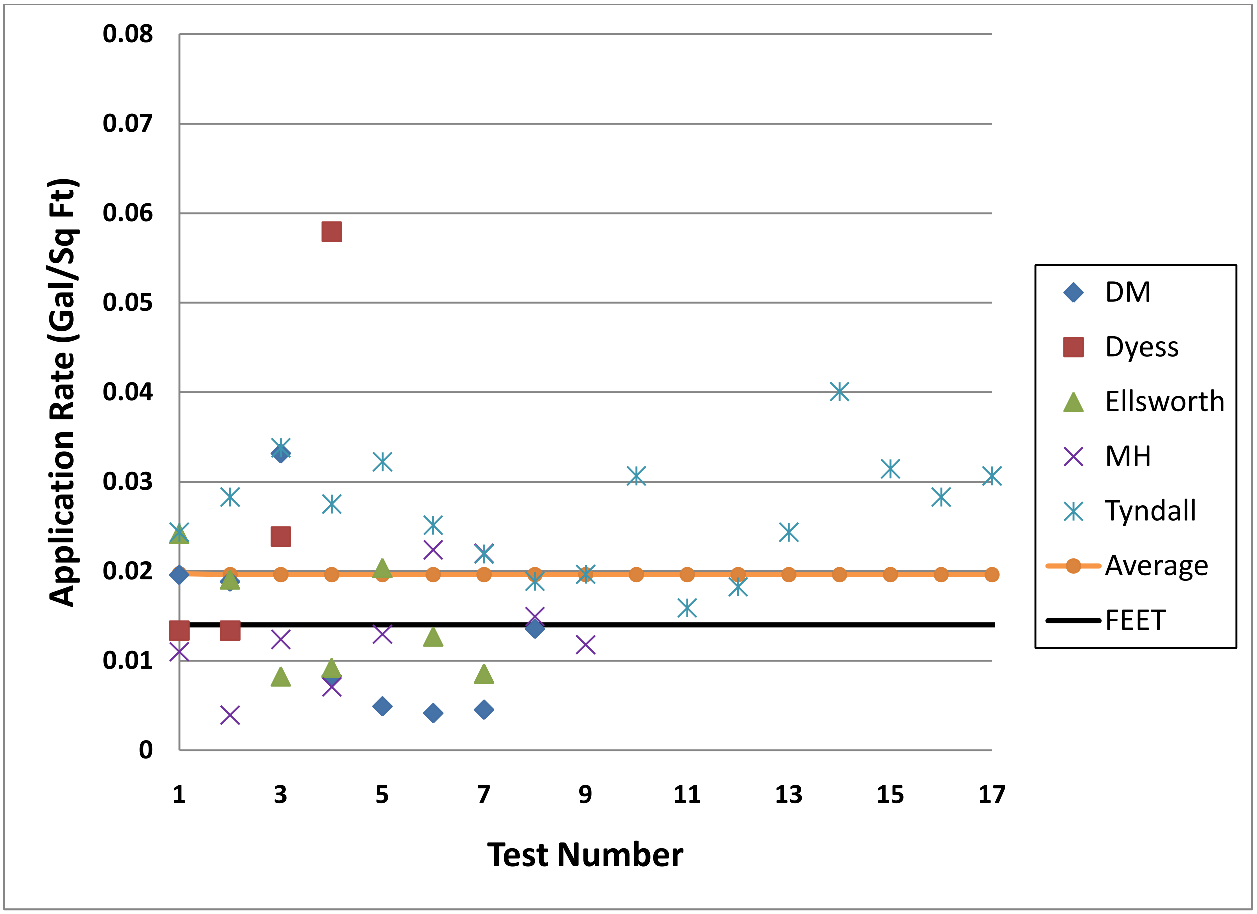


Figure 22. UHP Turret Fire Application Rates

Eleven fires were completed using the CAF bumper turret (Figure 23). UHP P-19c CAF turret operations averaged 0.038 gsf as compared to 0.028 gsf observed during the FEET study. The first fire completed by DM took 66 seconds to extinguish. The firefighter needed to reposition the vehicle to apply the foam to the area that was still involved in the fire and therefore, extended the extinguishment time. The second fire completed by Tyndall took longer than the others because the vehicle was repositioned twice during extinguishment. The firefighter conducting the testing at Tyndall was new and had no experience with CAF. The third and fourth fires show the improvement in extinguishment from the first two fires.

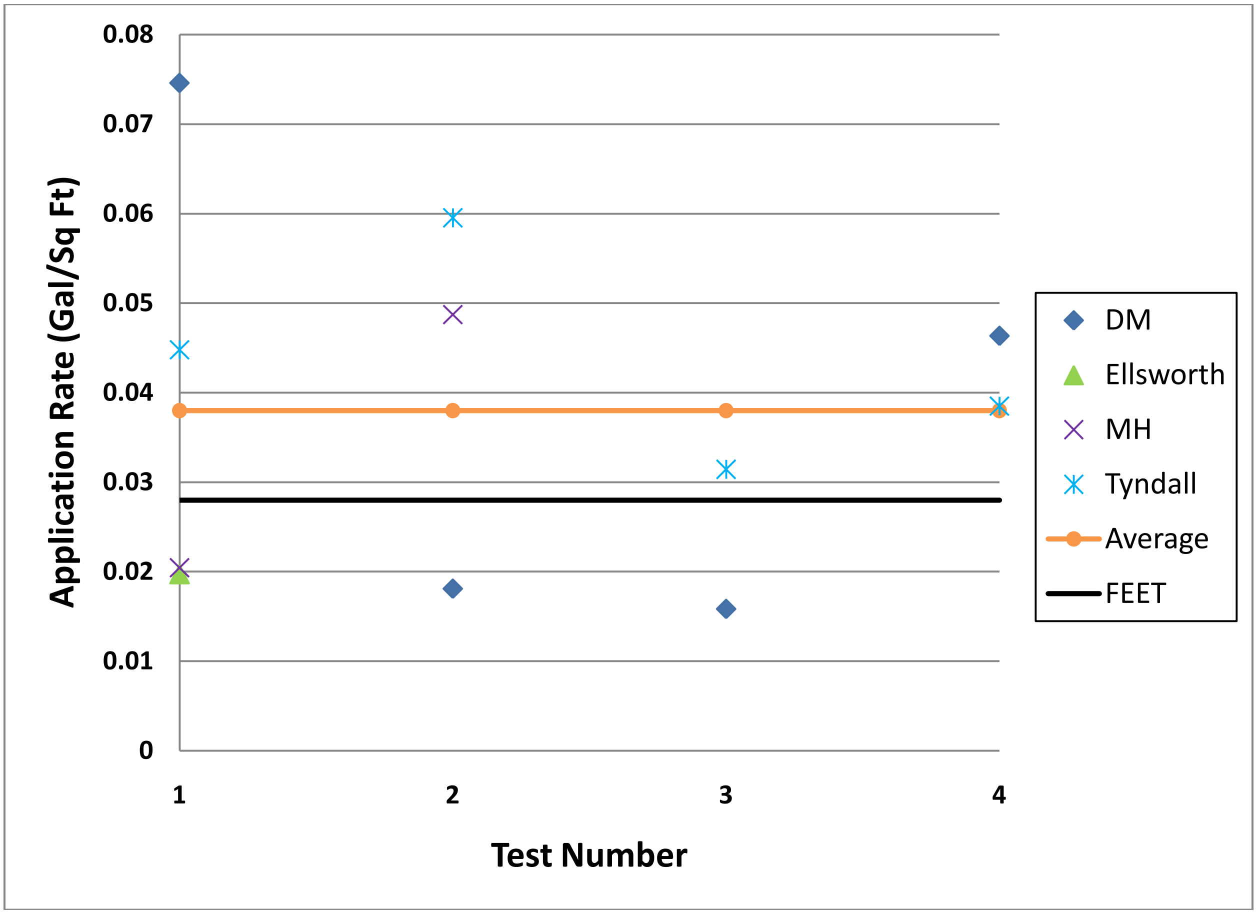


Figure 23. CAF Turret Fire Application Rates

Eleven fires were completed using the Hydro-Chem™ bumper turret (Figure 24). The UHP P-19c Hydro-Chem™ turret operations averaged 0.023 gsf as compared to 0.026 gsf observed during the FEET study. The majority of the fires was extinguished at or below the overall average with the exception of Tyndall fires 2-4. The first Hydro-Chem™ fire was completed by an experienced AFRL fire technician and the last three were completed by a new fire technician. Test 3 had the highest application rate. This was due to repositioning the vehicle twice during extinguishment.

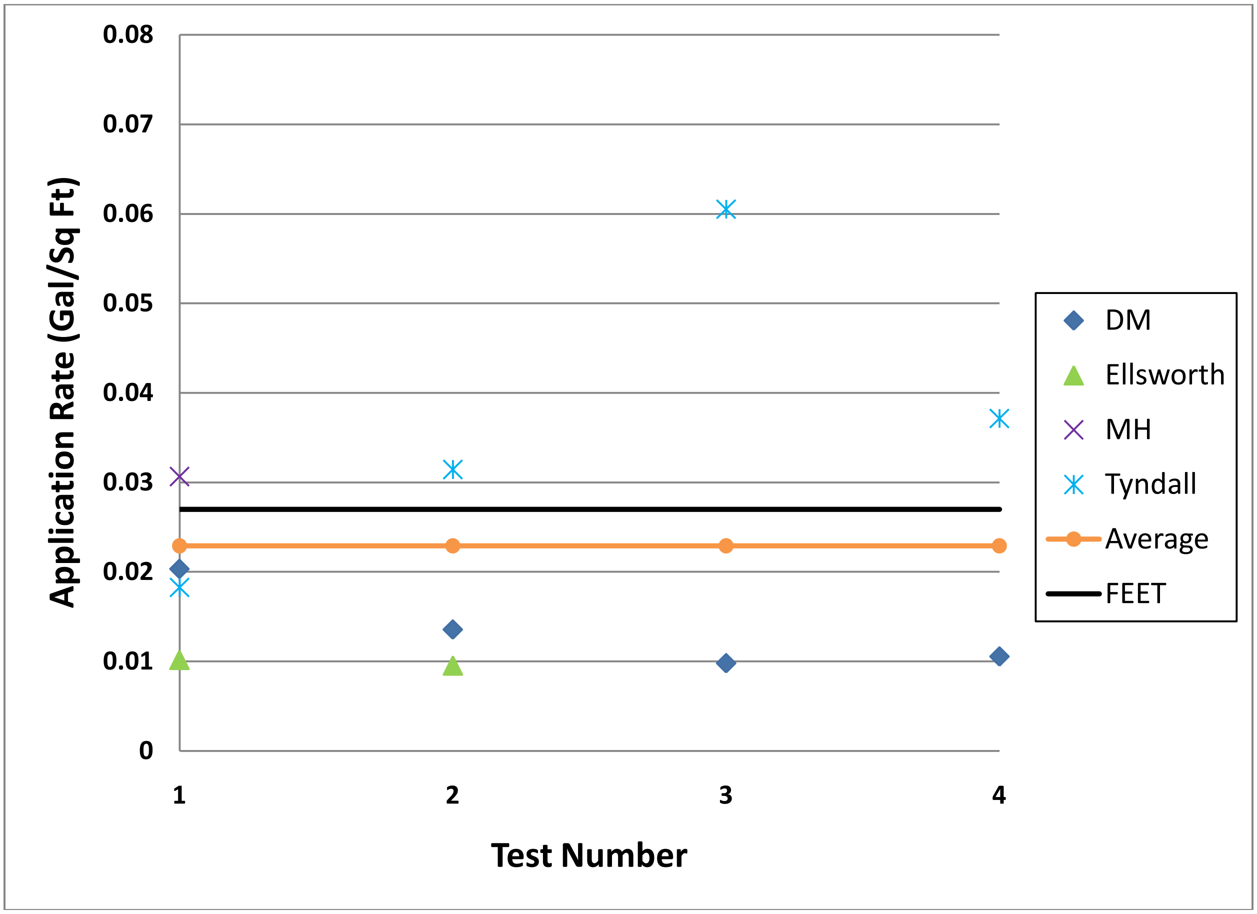


Figure 24. Hydro-Chem™ Turret Fire Application Rates

Twenty-one fires were completed using the UHP handline (Figure 25). The FEET study did not evaluate handline operations, no comparable data exists. Typically, application rates are improved by a factor of ten when compared to turret operations due to the firefighter having greater ability to control the application of the agent, resulting in less waste. The UHP handline average 0.0021 gsf application rate in comparison to 0.021 gsf for the UHP turret. Fires 3 and 4 at Dyess were higher than average due to the technique used by the firefighters, which included shutting off the agent flow as they advanced and applying agent to rocks on the side of the pit rather than focusing on the pool fire. Fire 4 at DM was almost three times the average. Review of the video shows a very poor foam blanket, which could indicate a problem with the foam proportioning system or that the foam switch was not activated for this fire.

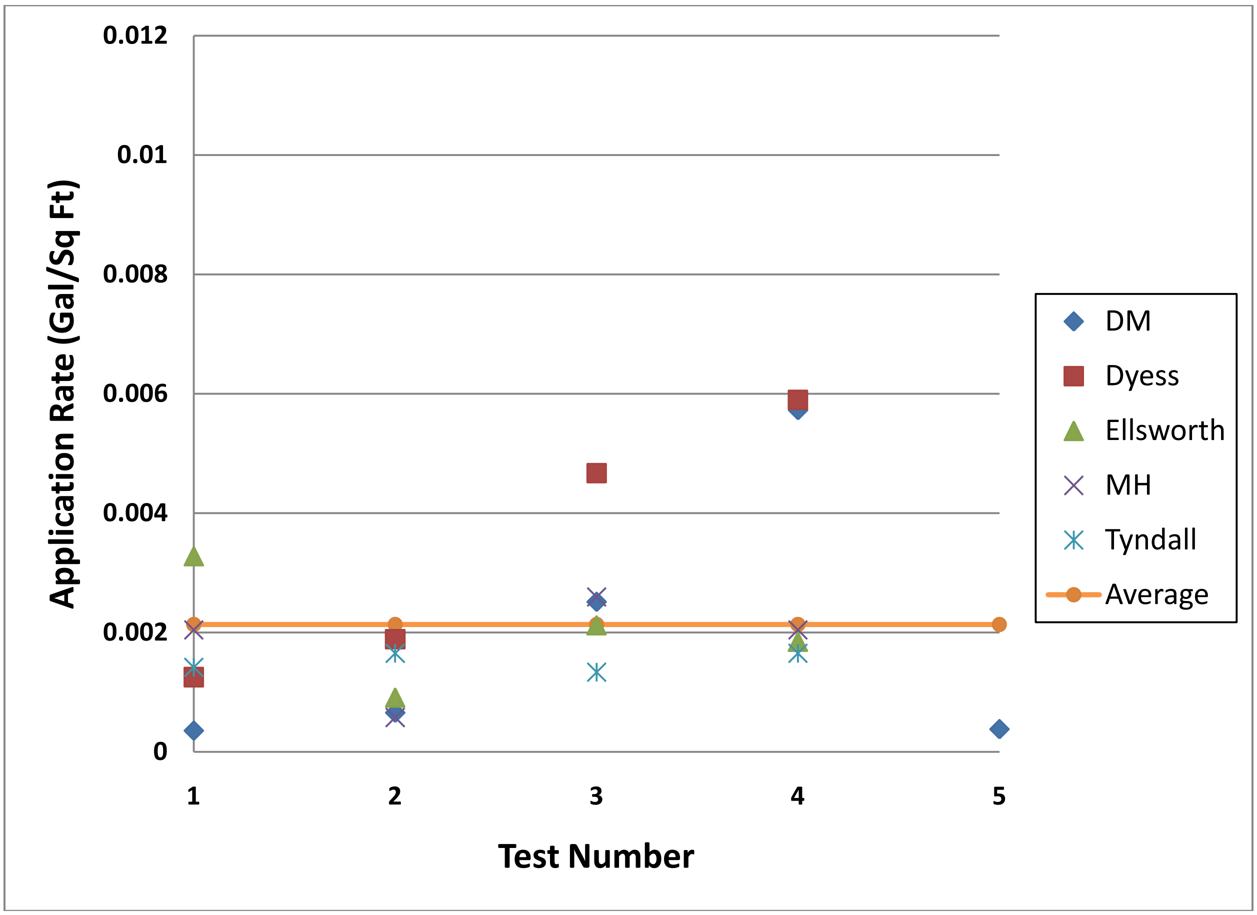


Figure 25. UHP Handline Fire Application Rates

Fifteen fires were completed with the CAF handline (Figure 26) with an average application rate of 0.0034 gsf (0.038 gsf for CAF turret). The single CAF fire at Dyess required more than twice the average agent. Review of the video showed a very large full pit fire that required over 87 seconds to extinguish. Handline tests required that 50% of the pit area be involved in the fire while this fire involved 100% of the pit area. The application rate was calculated based on the full pit area even though the test only required half the area.

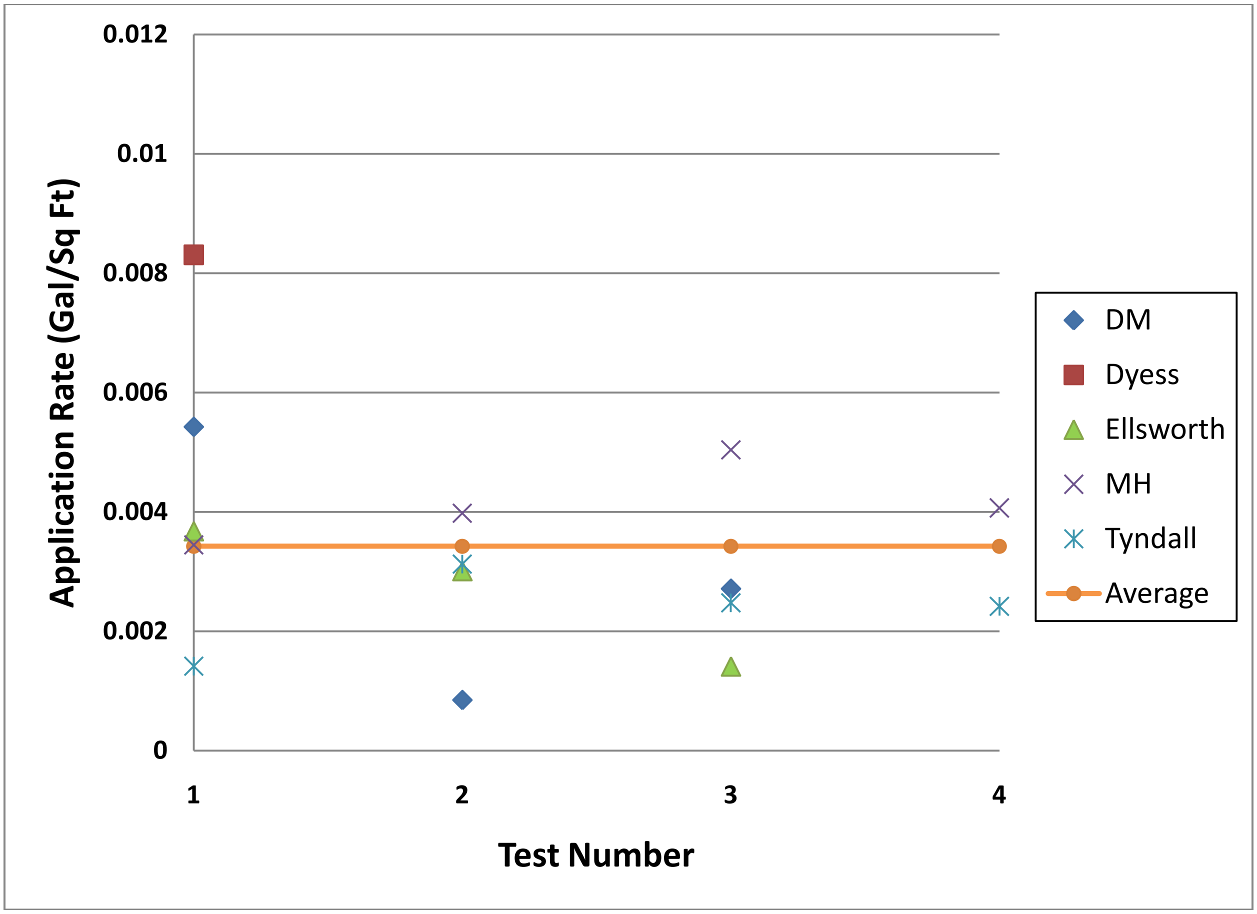


Figure 26. CAF Handline Fire Application Rates

Eighteen fires were completed with the Hydro-Chem™ handline (Figure 27) with an average application rate of 0.0030 gsf (0.023 gsf for the Hydro-Chem™ turret). Fire 3 at Ellsworth required twice the application rate because of difficulties with the bonded twin agent hose. The hose is only 100 feet long and requires careful prepositioning to assure the firefighter can reach all areas of the pit. During this fire, Ellsworth firefighters had to stop and reposition twice to reach the fire areas. They stopped a third time to get a kink out of the hoseline, which caused the agent to stop flowing. Fire 5 at MH required almost four times the agent to extinguish. Review of the video showed a very large intense fire with very little foam blanket.

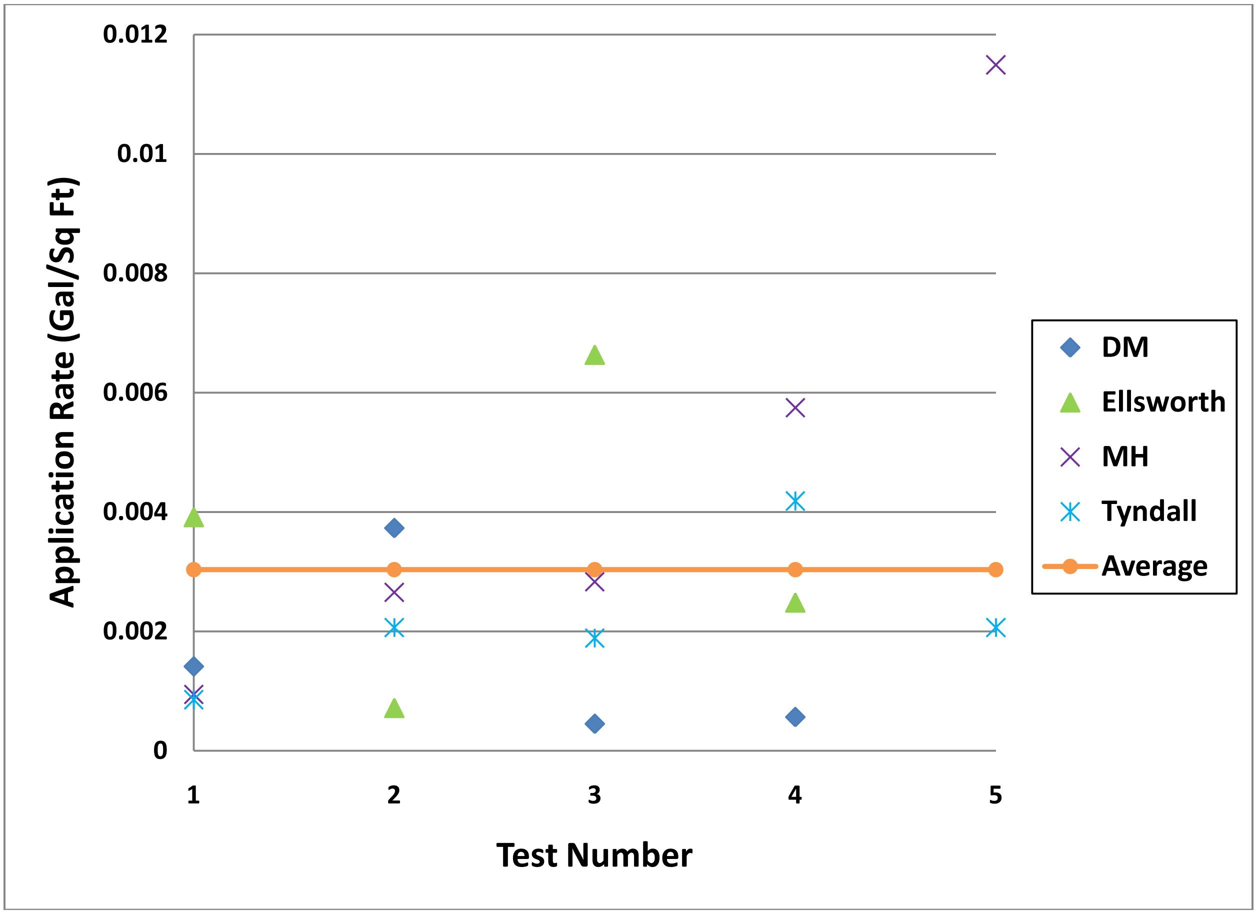


Figure 27. Hydro-Chem™ Handline Fire Application Rates

4.10 Cold Weather Operation

Four fires were completed by Ellsworth at temperatures near or below freezing with burning JP-8 on top of the frozen fire pit surface. The five vehicles were not modified with any additional cold weather protection for the new fire fighting system other that what already existed on the vehicle. Normal storage, maintenance and operational guidelines were followed for cold weather environments. While testing in sub-freezing temperatures was not required for the field evaluation, the results showed that the UHP P-19c was still effective at extinguishing fires using UHP and CAF plus dry chemical in the form of Hydro-Chem™ (Table 16). The handline fires were challenging for the firefighters as they had to extinguish the fires while walking on a sheet of ice. Review of the videos from each fire showed that the sub-freezing temperatures did not have any negative effects on agent stream characteristics or fire extinguishment effectiveness.

Table 16. Application Rate in Cold Weather

Date	Fire Type	Temperature (°F)	Application Rate (gal/sq ft)	Average Application Rate (gal/sq ft)
120908-1	UHP Handline	17	0.0019	0.002
120908-2	UHP Turret	19	0.009	0.020
121808	Hydro-Chem™ Handline	16	0.0025	0.003
010609	UHP Turret	35	0.0086	0.020

4.11 Design Issues Identified During Testing

4.11.1 Compressed Air Foam System

The air compressor used to generate the injection air for the CAF has to bleed down once the CAF system is shut off, which could take up to 90 seconds. The air compressor comes on when the pump is turned on and shuts off when the pump is turned off. The CAF handline or turret foam discharge can be turned on and off repeatedly without any problems as long as the pump is left on. Once the pump is turned off, the air compressor has to bleed the pressure to below 30 psi before it can be turned back on. This pressure cannot be dumped because of needing to separate the oil from the air, which can only be done slowly. Oshkosh consulted with the compressor manufacturer and designed the following solution:

> "I [Oshkosh] consulted with the compressor manufacturer and there are two things that allow us to engage with pressure in the tank. Because our reservoir is above the compressor the oil intake on the compressor will always be flooded with oil. This oil will be at or very near the pressure of the oil on the output side of the compressor. Due to this balance across the rotors of the compressor, that component is OK starting with pressure. Therefore, the high psi safety switch's primary function is to protect the power transmission device (in our case the electric clutch). Due to the fact that we have now nearly doubled the capacity of our clutch this may not be as much of a concern. Using the Davis (DM) truck we tuned the blowdown to give us the absolute minimum bleed down per the manufacturers recommendation. That is 45 seconds from operating pressure to 30 psi. This will help bleed down the pressure as quickly as possible when the system is shutdown. As you may have observed, the pressure drops quite rapidly at the beginning and slows down as the pressure drops. This will minimize the shock to the clutch in the event that the compressor is shut down and restarted quickly. To ensure that the clutch could handle this additional load we bypassed the high psi safety entirely and tried three different scenarios. One without discharging the turret we simply engaged CAFS, let the engine come up to speed and air pressure up to the set point then, turned CAFS off and back on again. Secondly, we did the same except we turned the pump off and then back on and restarted CAFS. In each of these scenarios the engine high idle signal is interrupted and the engine speed dips. The CAFS clutch, while taking slightly longer to engage, did achieve full lock up and system pressure was restored quickly. Finally we were discharging CAFS with the bumper turret and momentarily disengaged the CAFS switch and turned it back on. In this case the engine should not dip. The clutch was still able to lock up and rebuild system pressure."
>
> "Based on these observations, we [Oshkosh] are going to remove the 30 psi safety switch from the reservoir and supply a jumper plug for the connector. We [Oshkosh] do not recommend operating in this manner and will have a caution placed in the operators manual to avoid doing this. However, in an emergency situation the firefighter will be able to engage the CAFS compressor at any time the truck is in LOW pressure mode and FOAM is on. Due to the low likelihood of this scenario and the relatively light duty cycle that this particular system will see this should be an effective solution."

4.11.2 UHP Handline and Turret Operation

The UHP turret did not operate when the UHP handline was engaged. This issue was first identified at Dyess, verified at Tyndall and brought to the attention of Oshkosh. Below is Oshkosh's initial response:

> "What Mr. Slaughter has experienced can be attributed to the fact the high pressure supply valve is unable to open when the engine is at high idle because it is holding back up to 1600 psi. That is the reason the system has a 3 sec delay between the time a discharge is opened and the engine goes to high idle. As observed by Mr. Slaughter, the turret and handline can be activated and operated independently, but if both are to be used at the same time the sequence must be roof turret first then handline, not vice versa. With both the turret and handline discharging, if the turret is turned off it will be necessary to turn off the handline to allow the engine speed to come down and the pressure drop before reactivating the turret discharge. This scenario should not be seen during low pressure CAFS operations (*confirmed by AFRL*). UHP installations on additional P-19 retrofits or on new vehicles will be modified to include provisions which will eliminate the discharge sequencing procedure necessary on the first five P-19 UHP retrofit vehicles."

AFRL sent a message to all the bases warning of this issue so that the necessary safety precautions and training could be implemented. AFRL received strong concern from Dyess so we reevaluated the problem with our in-house mechanical engineers. AFRL proposed two simple modifications that would resolve the problem, which were proposed to Oshkosh. Oshkosh designed a relay switch to send a signal to the engine to drop the rpm whenever the turret was operated if the handline was engaged. This allowed the pressure to drop and actuator valve to open to discharge from the UHP turret. This caused a short (1-2 second) drop in pressure at the handline but did not affect flow and the handline operator did not lose function. Oshkosh ordered parts to fix all five vehicles and repairs were made in the field at each base by the base mechanics.

4.11.3 Pump and Roll in Handline Mode

Oshkosh installed a safety feature on the vehicle limiting handline operation during pump and roll. Pump and roll is a typical vehicle operation during turret discharge. Pump and roll allows for continued application of agent while the vehicle is moving. Oshkosh was concerned that firefighters could be injured while using the handlines if the vehicle was not in neutral with the parking brake applied. After consultation with AFCESA and the bases involved in field testing, AFRL requested that Oshkosh remove this feature as the firefighters thought operations were safer if they were given the ability to continue to apply agent with the handline while the vehicle was moving. Oshkosh refused to make this change even if the Air Force signed legal documents exempting Oshkosh from any liability. This issue was not resolved on any of the five vehicles but should be addressed in future vehicle specifications as this function is standard on other fire fighting vehicles.

4.11.4 Handline Operations and Problems with the Gear Shift

The gear shift on the UHP P-19c was not modified for the retrofit of the new fire fighting system. As mentioned above in Section 4.6.3, the vehicle must be in neutral with the parking brake applied for the UHP, CAF or Hydro-Chem™ handlines to operate. Occasionally during testing, the handline would not operate once the vehicle was moved into position to fight a fire. AFRL consulted with Oshkosh and determined that the gear shift did not always lock completely into neutral and the handle would have to be moved back and forth until neutral engaged and the valve opened to the handlines. This issue is related to the age of the vehicle and was outside the scope of the modifications to these vehicles.

4.11.5 Akron Brass Handline Nozzle Temperatures

AFRL noticed that the Akron Brass handline became very hot after a few minutes of operation. AFRL consulted with Oshkosh and was told that water recirculated through the pump to keep the pump from overheating when in low flow UHP handline operation. AFRL attached thermocouples to the nozzle to monitor temperature and determined that the pistol grip reached 130°F after three to five minutes of operation. The design of the Akron Brass handline nozzle flowed water through the uninsulated pistol grip and out the nozzle body. AFRL sent the nozzle back to Akron Brass and an insulative plastic coating was applied to the grip. AFRL retested the nozzle but obtained similar results. No additional modifications have been made to the nozzle to eliminate this issue.

4.11.6 Elkhart Brass Handline Nozzle Clogging

The Elkhart Brass handline nozzle clogs easily from small debris in the water and needed to be flushed several times during operation to function properly. Debris in the nozzle caused decreased pressure, flow and discharge distance. Elkhart Brass was consulted on the issue but no additional modifications were made to the nozzle.

4.11.7 Pump Gear Box Cooling

The Oshkosh TD was designed and fabricated to operate for short periods of time in order to evaluate the fire fighting systems; therefore, a cooling system for the pump gear box was not installed. The five UHP P-19c vehicles were supposed to be designed not only for test purposes but also to remain at the base as part of the response fleet. During the design of the UHP P-19c, this feature was overlooked by Oshkosh and, as a result, the pump could only be operated for a short period of time before overheating would occur. AFRL attached two thermocouples to the pump to monitor interior and exterior temperatures. The pump was cycled on for one minute then off for one minute in UHP mode for both the turret and handline. Measurements were made at the end of each cycle until the interior pump temperature reached 280°F. AFRL consulted with Oshkosh about installing a cooling system but determined that the modification would be too costly due to major redesigned considerations. Based on data, AFRL determined that the turret could be continuously operated to discharge one tank of foam (approximately 10 minutes) and the handline could continuously operate for one tank of water (approximately 50 minutes).

Future vehicles should have a cooling system installed so that the pump can run indefinitely when attached to a water source.

4.12 Field Demonstration Database

AFRL has prepared a separate database that includes all the fires, field data sheets and comments from the firefighters participating in the testing. The database can be searched by test type, date or location to easily review the video and associated information on that fire. Requests for a copy of the database should be made to the Defense Technical Information Center (DTIC) (http://www.dtic.mil) referencing AFRL-RX-TY-TN-2010-0032, Field Demonstration of a Centrifugal Ultra High Pressure (UHP) P-19 (Database).

5.0 CONCLUSIONS

1. While the Oshkosh TD pump experienced a failure early in testing, initial data showed that the overall pump performance exceeded the requirements established by the Air Force. The failure also identified a maintenance issue that was corrected in subsequent units and was written into the operations manual for the vehicle.

2. Foam proportioning using the plate and plunger system is not reliable and did not accurately meter the foam both with the Technology Demonstrator and UHP P-19c.

3. The new Darley six stage centrifugal pump performed as designed and no problems were encountered during testing.

4. The Elkhart Brass bumper turret system met the performance specifications designated by the Air Force while changes to the Akron Brass bumper turret are necessary to resolve several issues including overall height and reaction forces from the Hydro-Chem™ nozzle.

5. The Akron Brass handline nozzle reaches temperatures of 130°F and gloves should be worn at all times when operating the system.

6. The Elkhart Brass handline nozzle is prone to clogging and should be flushed on a regular basis to avoid problems with flow, pressure and discharge distance. Elkhart Brass has agreed to investigate the cause of this problem and find an engineering fix.

7. The controls on the UHP P-19c are simple to use and minimal training is required for the firefighter to gain proficiency based on the amount of time AFRL spent with each base during the initial familiarization period. Firefighters were using all six systems proficiently within the first two days.

8. Locating the retrofitted vehicles at five different bases provided a wide variety of experience, techniques and weather conditions, which expanded the demonstration of the technology beyond more controlled laboratory conditions at AFRL.

9. Minimal guidance should be required to integrate UHP technology into the other bases and training programs based on the amount of training provided to the four bases provided with modified vehicles.

10. The UHP and CAF turret and handline systems provided good expansion ratio and drain times indicating a good quality foam.

11. The UHP and CAF turret and handline systems showed excellent discharge distance and exceeded the minimum NFPA requirements. The UHP turret provided a 50% improvement in discharge distance compared to the NFPA minimum requirements for bumper turret systems.

12. AFRL testing of the UHP turret at 4%, 5%, and 6% of Type 3 foam concentrate showed that the amount of 3% foam concentrate could be reduced from 6% to 4% without affecting fire fighting performance or burnback protection.

13. Pump cycle testing did not show any signs of wear or damage to the pump. With the exception of Ellsworth, all four pumps had been cycled on and off over 600 times without failure or the need for maintenance. As of the date of publication, all five pumps have been in operation without any problems.

14. The UHP handline consistently extinguished running and compartment fuel fires. UHP foam and water used approximately 50% less agent by weight compared to Halon 1211. UHP foam and water is an acceptable agent for three dimensional and hidden fuel fires, such as those in engine nacelles.

15. UHP, CAF and Hydro-Chem™ were more efficient than low pressure foam and water application techniques. UHP showed superior performance compared to CAF or Hydro-Chem™ in both turret and handline operations.

16. UHP and Hydro-Chem™ agents performed well in sub-freezing environments. No issues related to cold weather were identified with the UHP P-19c.

17. Several engineering issues were identified during testing and all but one (pump and roll using the handline) was resolved with the cooperative efforts of Oshkosh and AFRL.

6.0 RECOMMENDATIONS

1. UHP foam and water should be considered a suitable replacement for dry chemical and gaseous agents used for hidden compartment and running fuel fires.

2. UHP turret foam and water should be considered a suitable replacement for low pressure, high flow roof turrets.

3. UHP handline foam and water should be considered a suitable replacement for low pressure, high flow handline nozzles.

4. Continue to meter the Type 3 AFFF concentrate at 3% for CAF, 4% for UHP turret and 6% for UHP handline operations.

5. Additional testing in cold weather environments should be conducted to confirm the performance of all handline and turret systems.

6. Replace the snap ring every time the centrifugal pump is disassembled to prevent the impeller from coming loose and causing pump failure.

7. Use an electronic foam proportioning system with proven accuracy to meter the foam, especially if using the UHP and CAF turret and handline systems, which require three different proportioning rates.

8. Redesign of the Akron Brass bumper turret or the method of attaching the Hydro-Chem™ nozzle to the turret is necessary to lower the overall profile and eliminate the reaction force caused by the Hydro-Chem™ nozzle.

9. If used with high temperature water, the Akron Brass handline nozzle needs to be insulated so that the nozzle can be handled without gloves.

10. Install a cooling system for UHP pumps to prevent overheating.

11. The Elkhart Brass handline nozzle needs to be re-engineered to eliminate clogging at the nozzle discharge.

12. Speed proportional joysticks should be integrated into any fire fighting system as they give the firefighter greater control over the turret operation.

13. Continue pump cycle testing at all bases with the UHP P-19c so that additional time can be logged on the centrifugal pumps.

14. The CAF or Hydro-Chem™ systems should be capable of being turned on and off repeatedly without damage to the air compressor system.

15. The turret and handline systems should be capable of operating separately or simultaneously and switch on and off without affecting discharge.

16. The vehicle should have pump and roll capability in handline mode in order to reposition the vehicle while maintaining agent flow.

7.0 REFERENCES

1. National Fire Protection Agency, NFPA 412: Standard for Evaluating Aircraft Rescue and Fire-Fighting Foam Equipment, 2009 Edition.

2. Military Specification, MIL-F-24385F: Fire Extinguishing Agent, Aqueous Film Forming Foam (AFFF) Liquid Concentration, For Fresh and Sea Water, 7 January 1992.

3. McDonald, Michael and Hawk, John. Evaluation of a Centrifugal Pump for Ultra High Pressure and Compressed Air Foam Fire Fighting. Defense Technical Information Center. AFRL-RX-TY-TR-2008-4580. July 2009.

4. Verbal Quote from Pat DeBound of Depco Pumps, December 17, 2008.

5. Verbal Quote from Paul Darley, President, W. S. Darley & Co. December 17, 2008.

6. McDonald, Michael, Dierdorf, Douglas, Kalberer, Jennifer, and Barrett, Kimberly. Fire Extinguishing Effectiveness Tests. Defense Technical Information Center. AFRL-ML-TY-TR-2004-4554. Nov 2004.

7. Menchini, Christopher, Dierdorf, Douglas, Kalberer, Jennifer, McDonald, Michael., Cozart, Kristopher., Casarez, Adrianna, and Carr, Virgil. The Development and Design of a Prototype Ultra High Pressure P-19 Firefighting Vehicle. Defense Technical Information Center. AFRL-ML-TY-TR-2007-4525. Feb 2007.

8. National Fire Protection Agency, NFPA 414: Standard for Aircraft Rescue and Fire-Fighting Vehicles, 2007 Edition.

9. Air Force Technical Order 36A12-8-17-1. Aircraft Crash and Structural Firefighting Truck: Operation and Operator Maintenance Instructions. USAF Type A/S32P-19 Technical Manual: 11 January 1988.

10. Air Force Research Laboratory. Minimum Performance Requirement for Air Force Flightline Fire Extinguishers: Extinguishing Performance Against 3-Dimensional and Hidden Fires. Defense Technical Information Center. AFRL-ML-TY-TR-2002-4540. May 2002.

11. Bowman, H., Davidson, R., Verdonick, D., Darwin, R., Hawk, J., Dormer, K., and Mullenhard, P. ESTCP Demonstration Plan Qualification of an Acceptable Alternative to Halon 1211 DoD Flightline Extinguishers ESTCP Thrust Area: Pollution Prevention (Material Substitution). Draft. Naval Air Warfare Center Weapons Division. ESTCP 06-D-PP3-026. April 2008.

12. Dierdorf, D and J. Kiel. Halon Flightline Extinguisher Evaluation: Data Supporting Standard Development. Defense Technical Information Center. AFRL-ML-TY-TR-2005-4583. Oct 2005.

APPENDIX A - Memorandum from W.S. Darley & Co on the CRADA TD Pump Failure

In August, 2008 AFRL initiated a program to modify five P-19s with the Darley centrifugal pump technology and conduct a series of tests under field conditions including foam quality, pump cycling and fire extinguishment effectiveness. In the months following the conclusion of the Oshkosh testing of the first centrifugal pump, Darley investigated the cause of the pump failure and designed engineering and maintenance practices to assure this problem would not happen with subsequent units. The following tests were completed by Darley to analyze pump performance and identify potential failure modes:

1. The pump can withhold a hydrostatic pressure of 1950 psig for 15 minutes.

2. For the pump's high pressure performance point, the pump can attain 1240 psig while flowing 300 gpm through its 6th stage discharge. To operate at this test point, the pump must be provided with shaft horsepower at 3550 rpm and the 1st stage discharge must be closed.

3. For the pump's low pressure performance point, the pump can attain 198 psig while flowing 300 gpm through its 1st stage discharge. To operate at this test point, the pump must be provided with shaft horsepower at 3550 rpm. The 0.1360" orifice will flow approximately 20 gpm which will experience a 50°F increase in temperature.

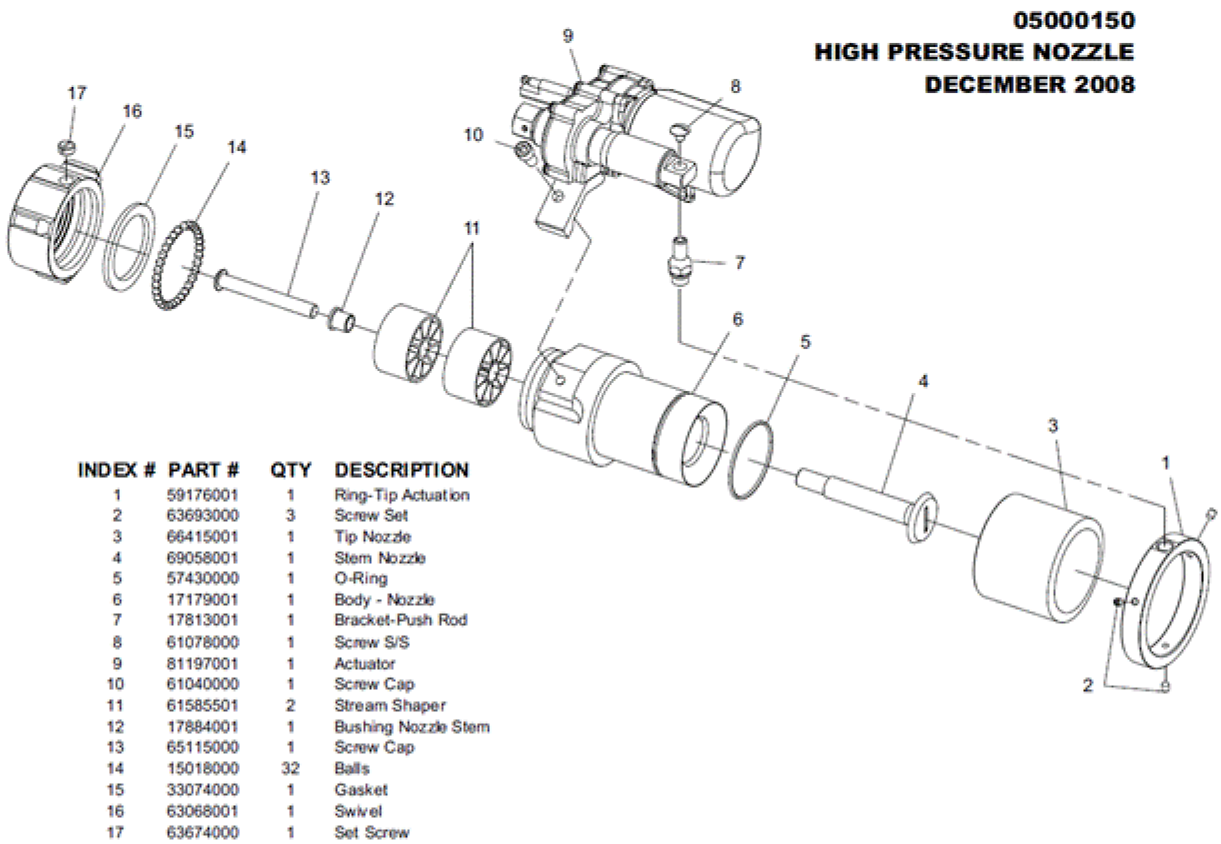
4. The pump was endurance tested for 20 hours of accumulated time by undergoing a repeated cycle of operating at its high pressure performance point for 5 minutes followed by being stopped for 5 minutes. This cycle was repeated intermittently (10 hour days) until the accumulation of time that it was being operated at its high pressure performance point equaled 20 hours. The results of the endurance test showed we could lengthen the life of the large mechanical seal by adding the element Antimony to the carbon pusher ring. After the endurance test the pump was still functional.

5. The pump was drained of water and run dry for a period of 5 minutes at 3550 rpm. Running dry is not a recommended practice but the test was conducted to see if the seal withstood the abuse. After the running dry test, the pump passed a dry vacuum test by being able to hold a static vacuum of 22 inches of mercury for 5 minutes.

6. The wear components of the pump consist of the four gear box bearings, three oil seals, two mechanical water seals and 80W-90 gear box lubricant. The estimated time to replace all of these wear components on a pump that has been removed from the truck is 2 hours.

7. The estimated time to failure (calculated L_{10} life) on the wear components is 1,375 hours when operated at the high pressure performance point.

APPENDIX B - Correspondence from Elkhart Brass on UHP Nozzle Redesign



INDEX #	PART #	QTY	DESCRIPTION
1	59176001	1	Ring-Tip Actuation
2	63693000	3	Screw Set
3	66415001	1	Tip Nozzle
4	69058001	1	Stem Nozzle
5	57430000	1	O-Ring
6	17179001	1	Body - Nozzle
7	17813001	1	Bracket-Push Rod
8	61078000	1	Screw S/S
9	81197001	1	Actuator
10	61040000	1	Screw Cap
11	61585501	2	Stream Shaper
12	17884001	1	Bushing Nozzle Stem
13	65115000	1	Screw Cap
14	15018000	32	Balls
15	33074000	1	Gasket
16	63068001	1	Swivel
17	63674000	1	Set Screw

Figure B-1. Elkhart Brass UHP Nozzle Parts Schematic

ELKHART BRASS MFG. CO., INC.
1302 WEST BEARDSLEY AVENUE • P.O. BOX 1127 • ELKHART IN 46515 • (574) 295-8330 • FAX (574) 293-9914

December 8, 2008

Jennifer Kalberer
Air Force Research Lab
Tyndall Air Force Base, FL

REF: High Pressure Nozzle Field Failures

Jennifer:

This is in response to the various email reports of nozzle failures from Davis-Monthan and Mountain Home AFB's. Last week we succeeded in reproducing the failure in our laboratory, and feel that we can finally provide an accurate assessment of cause. The tests consisted of cycling the nozzle pattern sleeve from wide fog to straight stream repeatedly until failure. Testing was conducted with no flow or fluid pressure applied. Failed parts appeared identical to the field failure parts, so we are quite confident that the laboratory failure mechanism was identical to that of the field failures.

Laboratory failure occurred after 43 fog/straight stream cycles, and is attributed to the fact that the push rod bracket (Item 7, part #17813001 on attached parts drawing) is .060 inch too short for the assembly. When screw 8 is tightened down against the end of the push rod bracket 7, the pushrod of actuator 9 is placed in a bind. It is this binding that apparently causes the very early failure of bracket 7 and tip actuation ring 1.

A comparison test was conducted with new parts, and screw 8 adjusted so that it just came in contact with the stepped surface of the pushrod end, thus eliminating any binding. The nozzle was put through 1000 cycles with no signs of part damage or excessive motor loading.

The push rod design error occurred in the early prototype phase of the project, but the effect was not realized until recently because the earlier nozzles, including those tested at Tyndall, were assembled by the design engineer. He was aware of the short bracket condition, and carefully adjusted and secured the screw to not cause binding. The more recent nozzles built, including those shipped to Oshkosh for field testing, were assembled by an intern who had no knowledge of the design discrepancy. In those assemblies the head of screw 8 was apparently tightened all the way down to make contact with the push rod end.

We have corrected the push rod bracket length and assigned new part number 18370001. Also, for reasons of manufacturing economy, we have integrated the features of tip actuation ring 1 (part #59176002) into nozzle tip 3 (part #66415001). We will be sending new parts to Davis-Monthan and Mountain Home later this week. Please accept our apology for the inconvenience caused.

Sincerely,

Jim Trapp, P.E.
Chief Engineer

APPENDIX C - Oshkosh Engineering Technical Reports

OSHKOSH®

ENGINEERING TECHNICAL REPORT

ETR NO: T 447

DATE OF INCIDENT: 4/29/08

MODEL: UHPW P-19 #1

VEHICLE S/N: 28227

VEHICLE MILES: N/A

VEHICLE OPERATING HOURS: N/A

PROJECT NO.: 101137

REQUESTED BY: DAVE STEINBERGER

SUBJECT: UHPW Water, Foam, & CAFS Flow Rates

REASON:
This report is to summarize all of the agent flow testing during testing of P19 #1 with the Ultra High Pressure Water (UHPW) system installation.

OBJECTIVE:
The discharges require the following agent flow rates.

DISCHARGE	AGENT FLOW (GPM)	PRESSURE (PSI)	CAFS AIR FLOW (SCFM)
High Pressure Bumper Turret	> 300	Turret Inlet > 1100	n/a
Low Pressure Bumper Turret	> 300	??	> 200
High Pressure Handline	> 20	Nozzle Inlet > 1300	
Low Pressure Handline	> 45	??	> 45

The three foam orifices must be sized for the following discharges and NFPA 412 allowable percentages.

POPPET LOCATION #	DISCHARGE	FOAM %
1	Low Pressure Bumper Turret	2.8 – 3.5
2	High Pressure Bumper Turret	5.5 – 7.0
4	High & Low Pressure Handline	Low Pressure: 2.8 – 4.0 High Pressure: 5.5 – 8.0

TECHNICIANS: Walter Wucki

REPORT BY: John Woelfel JW

DATE: 5/5/08

TIME TAKEN: 20 Days

DISTRIBUTION: L. Maxfield, D, Steinberger, C. Voight, J. Morrow, T. Meihlan, D. Mansfield, & W. Wucki

CONCLUSIONS:

Low Pressure Bumper Turret

All of this testing was done with 2" diameter swivels supplying the Williams Hydra-Chem Nozzle (photo #5). A 1.34" diameter orifice was installed in the low pressure branch (photo #6) to drop the pressure from 193 psi out of the pump to 149 psi downstream of the orifice. This pressure drop made it possible for air to be injected into the agent stream. The final agent flow was 316 gpm with a nozzle inlet static pressure of 88 psi and the CAFS air flow was 195 scfm. 195 scfm was the maximum air flow (no orifice in CAFS line) that the CAFS compressor could produce at a reservoir pressure of 160 psi. The foam percentage was 3.3% with a 0.440" diameter orifice installed in poppet # 1.

High Pressure Bumper Turret

All of this testing was done with an Akron 3450 turret with an Akron 1550 nozzle (photo #5). The turret was originally equipped with a 0.56" diameter nozzle. This was too restrictive to flow the required 300 gpm. The nozzle diameter was increased to 0.58" and this allowed the turret to flow 305 gpm with a turret inlet static pressure of 1260 psi. The foam percentage was 6.3% with a 0.720" diameter orifice installed in poppet # 2.

Low Pressure Handline

The low pressure handline consisted of 100' of 1" diameter dual agent hose with a Williams Hydra-Chem nozzle on the end (photo #3). A 0.590" diameter orifice was installed in the piping upstream of the CAFS air injection point (photo #4). This orifice provided the required pressure drop for the CAFS induction. The CAFS air needle valve was wide open for all of this testing. The truck was shipped with an air flow of 47 scfm which provided a agent flow rate of 47 gpm and a nozzle inlet static pressure of 50 psi. This data was recorded with the hose unreeled. The foam percentage was 3.2% with a 0.173" diameter orifice installed in poppet # 4.

High Pressure Handline

The high pressure handline consisted of 150' of 0.75" diameter hose with an Akron pistol grip nozzle #4803 (photo #1). A 0.219" diameter orifice was installed in the hose fitting on the high pressure branch of the pump (photo #2). The agent flow rate was 23 gpm with a nozzle static inlet pressure of 1190 psi. This data was recorded with the hose unreeled. The foam percentage was 6.5% with a 0.173" diameter orifice installed in poppet # 4.

The table on page #7 also gives all the pertinent flow data of the truck as shipped to Tyndall AFB. The tables on pages #8 include all of the flow data acquired during this testing. The rows highlighted in yellow are the final configurations of each discharge.

TEST PARTICULARS

SYSTEM SETUP

Before testing began, the water and CAFS systems were setup to the following parameters:

1) The CAFS compressor clutch was burnished with 60 apply and release cycles at idle.

2) While flowing the CAFS handline, the pressure regulator on the CAFS compressor was set to 160 - 170 psi.

3) The high pressure turret was tested first. While the high pressure turret is flowing, the main system relief pilot valve in the low pressure stage was turned off. After the correct flow rate and pressure was obtained, the pressure in the low pressure branch was recorded. While flowing the high pressure handline, the main system relief was set at 5 – 10 psi higher than the pressure obtained while discharging the high pressure turret. This value was in the 200 – 210 psi range.

4) The engine electronic governor was set to 2100 engine rpm with CAFS turret discharging.

5) The pressure relief valve downstream of high/ low valves was set such that it did not open while flowing the high pressure turret.

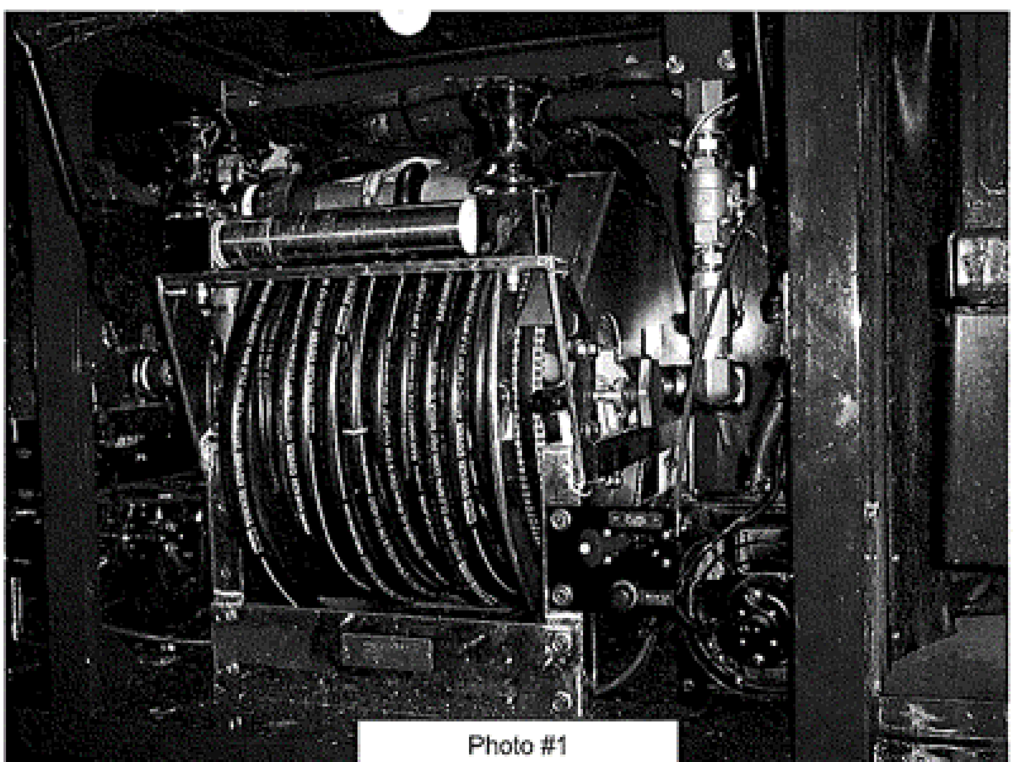
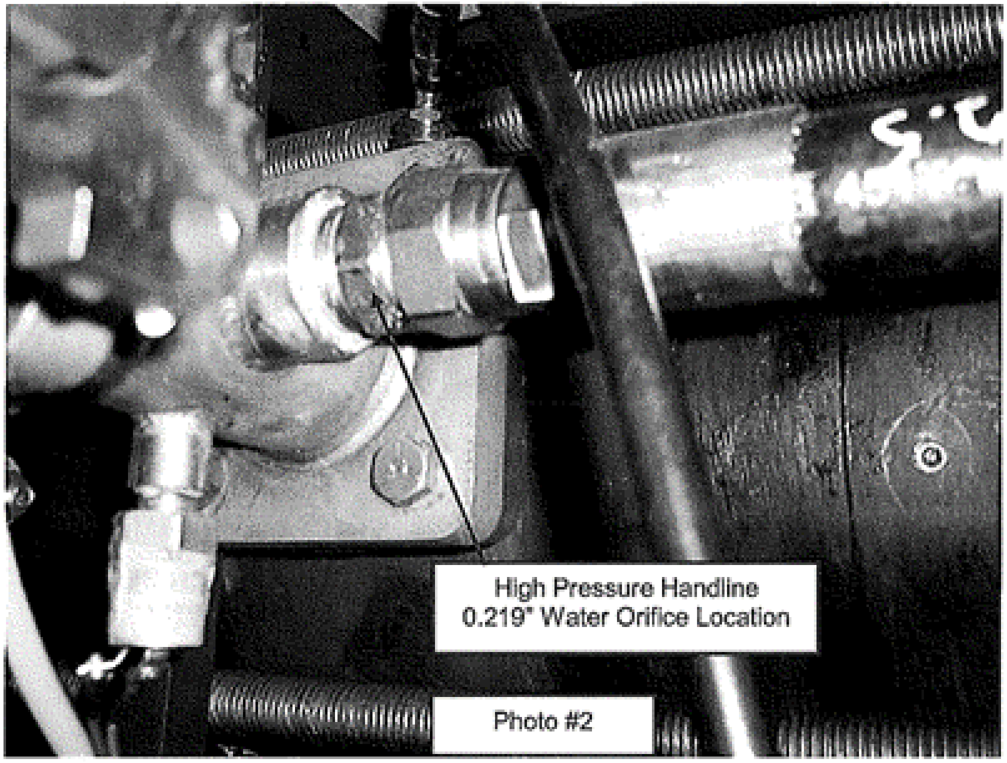


Photo #1
High Pressure Handline


High Pressure Handline
0.219" Water Orifice Location
Photo #2

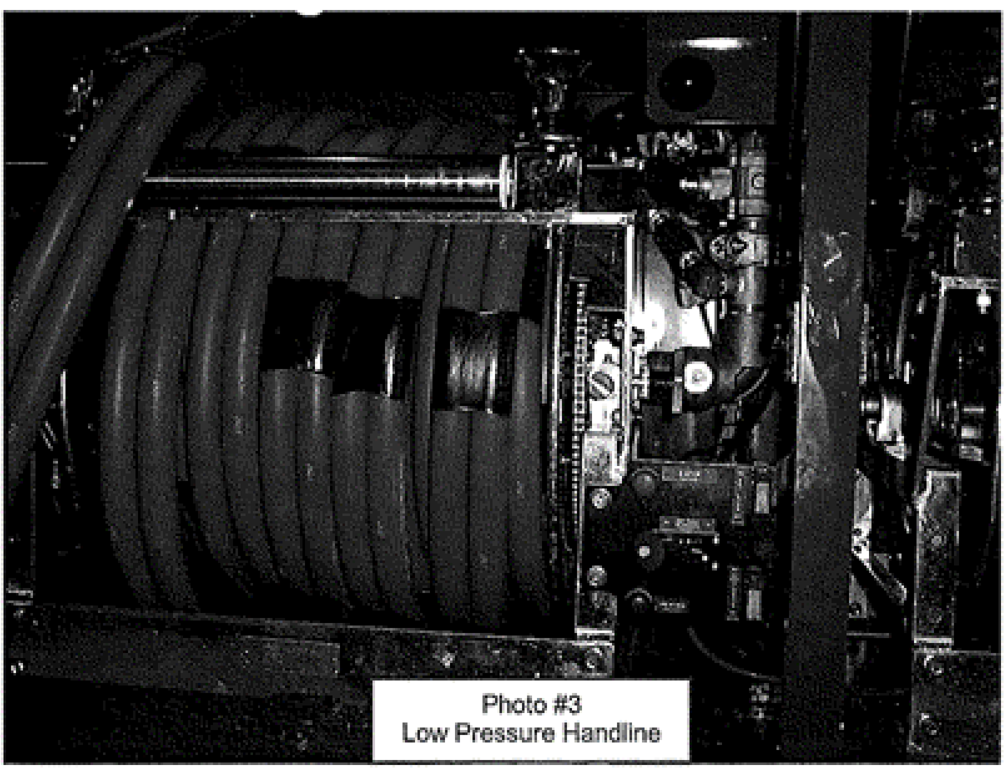
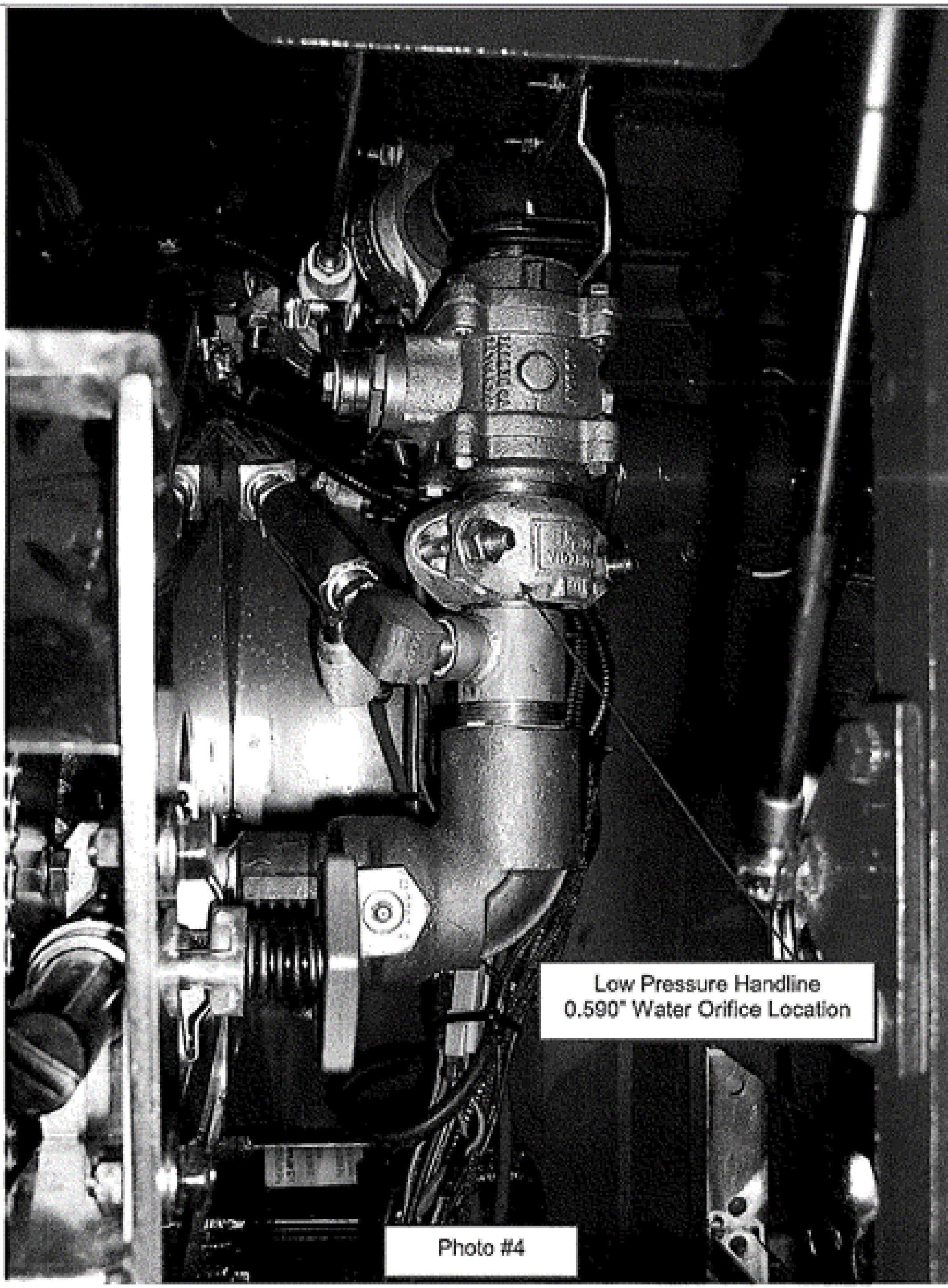


Photo #3
Low Pressure Handline


Low Pressure Handline
0.590" Water Orifice Location
Photo #4

P-19 #1 UHPW WATER SYSTEM DATA 4/15/2008

HP TURRET AKRON 3450 BUMPER TURRET WITH AKRON 1550 NOZZLE AND 0.58" NOZZLE
LP TURRET OTC 2" SWIVEL SYSTEM WITH WILLIAMS HYDRA-CHEM NOZZLE
LP HANDLINE 100' OF 1" HOSE WITH WILLIAMS HYDRA-CHEM NOZZLE
HP HANDLINE 150' OF 0.75" HOSE WITH AKRON PISTOL GRIP #4803 NOZZLE

Foam Plate Location	Function	Foam Flow (GPM)	Total Flow (GPM)	Foam %	Foam Orifice (" Dia.)	Water Orifice (" Dia.)	High Press Branch (PSI)	Low Press Branch (PSI)	Nozzle Press (PSI)	Pump Speed (RPM)	CAFS Airflow (SCFM)
Poppet 2	HP Turret	19.2	305	6.3%	0.720	none	1280	205	N/A	3580	N/A
Poppet 1	LP Turret	10.3	316	3.3%	0.440	1.340	1560	193	88	3554	195
Poppet 4	LP Handline	1.5	47	3.2%	0.173	0.590	1560	210	50	3586	47
Poppet 4	HP Handline	1.5	23	6.5%	0.173	0.219	1560	210	1190	3622	N/A

OSHKOSH®

ENGINEERING TECHNICAL REPORT

ETR NO: T 445

DATE OF INCIDENT: 4/29/08

MODEL: UHPW P-19 #1

VEHICLE S/N: 28227

VEHICLE MILES: N/A

VEHICLE OPERATING HOURS: N/A

PROJECT NO.: 101137

REQUESTED BY: DAVE STEINBERGER

SUBJECT: TILT TABLE & WHEEL WEIGHTS TEST

REASON:
This is the first P-19 that has been retrofitted with the Ultra High Pressure Water (UHPW) system.

OBJECTIVE:
Determine the static side slope stability of the UHPW P-19. The tilt table test procedure will follow the one recommended in SAE J2180. The vehicle will be chained to the tilt table around the frame to restrain it from complete rollover. The appropriate chain slack will prevent complete rollover while allowing enough upward wheel travel to obtain the rollover point.

Measure the wheel weights of the vehicle.

CONCLUSIONS:
The truck passed the 26.5° side slope stability requirement.

A summary of the results from the tilt table testing are given in the table below with a complete tabulation of the test data given in the *Test Particulars* section of this report.

Tested Configuration	Rollover Angle with Left Side Downhill	Rollover Angle with Right Side Downhill
Production	28.0°	29.3°

Loading information and wheel weight data is given in the *Test Particulars* section of this report.

TECHNICIANS: Walter Wucki

REPORT BY: John Woelfel JW

DATE: 5/5/08

TIME TAKEN: 1 Day

DISTRIBUTION: L. Maxfield, D, Steinberger, C. Voight, J. Morrow, T. Meihlan, D. Mansfield, & W. Wucki

TEST PARTICULARS

UHPW P-19 #1 TILT TABLE TEST RESULTS
VIN #28227

Configuration *	1	1
Side Downhill	Right	Left
Vehicle GVW	33660 lbs	33660 lbs
Tire Pressure	60 psi	60 psi
First Tire to Lift	#2 Left	#2 Right
Angle First Tire Lifted	29.3°	28.0°
Rollover Angle	29.3°	28.0°

*** Configurations Tested**

Configuration #1: After UHPW retrofit.

TESTED CONFIGURATION & LOADING

The truck tested had the following configuration:

1) UHPW system installed
2) Akron bumper turret
3) 150' long High Pressure hosereel in front right side compartment
4) 100' long dual agent low pressure hosereel in middle right side compartment
5) Nitrogen bottle in upper right side compartment
6) Dry-chem tank (empty) in front centerbody compartment

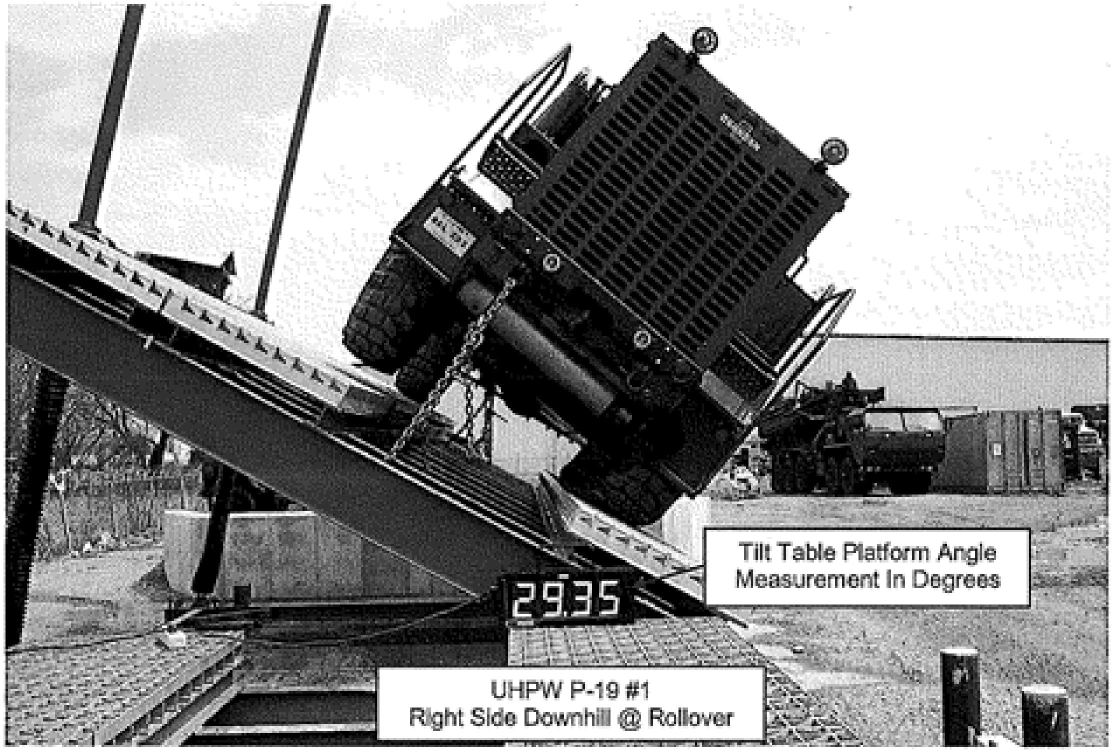
The fuel tank was full for all of the measurements. No driver or passenger's were on board for any of the measurements.

VIN # 28227 UHPW P-19 #1 WHEEL WEIGHTS

Loading Configuration**	A	B	C	D
Front Right Wheel (lbs)	5350			7850
Front Left Wheel (lbs)	5480			8200
Total Front Axle (lbs)	10830			16050
Rear Right Wheel (lbs)	6090			8610
Rear Left Wheel (lbs)	6360			9000
Total Rear Axle (lbs)	12450			17610
Total Left (lbs)	11840			17200
Total Right (lbs)	11440			16460
Total Vehicle (lbs)	23280	31820	33160	33660

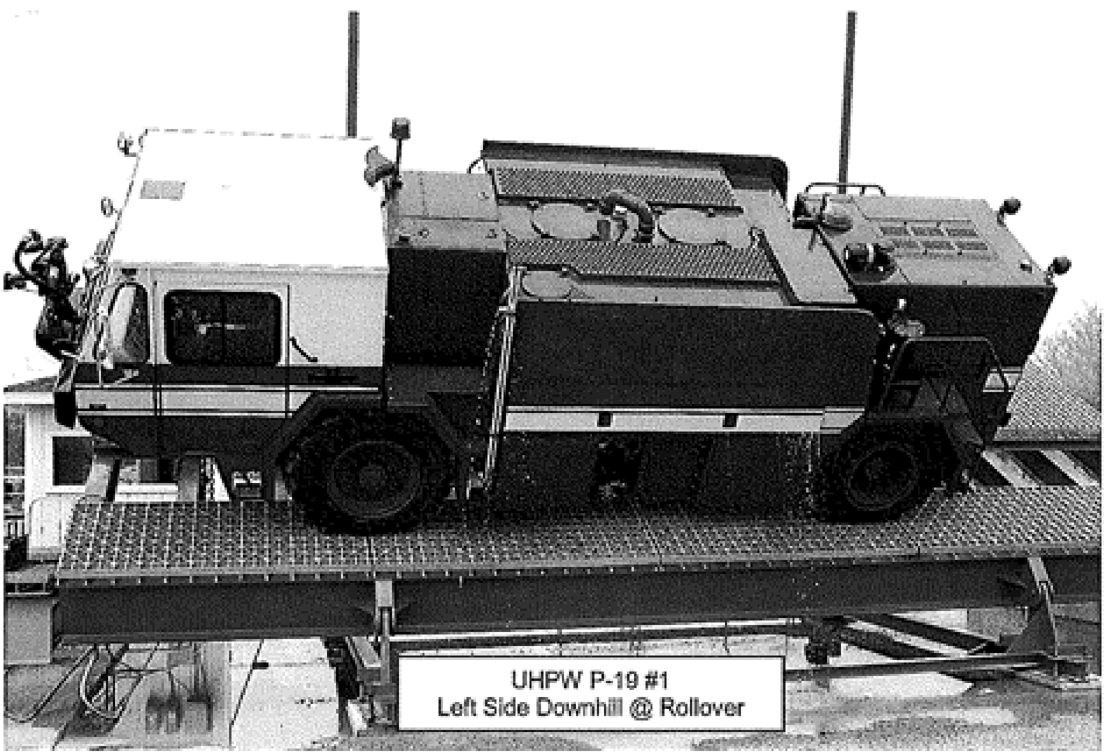
****Loading Configurations:**

A) Water, foam, & dry chemical tanks empty
B) Water tank full. Foam & dry chemical tank empty. Calculates to 1025 gallons of water capacity.
C) Water & foam tanks full. Dry chemical tank empty. Calculates to 160 gallons of foam capacity.
D) Water & foam tanks full. 500 lbs of sandbags added adjacent to dry chemical tank to simulate a full agent tank.

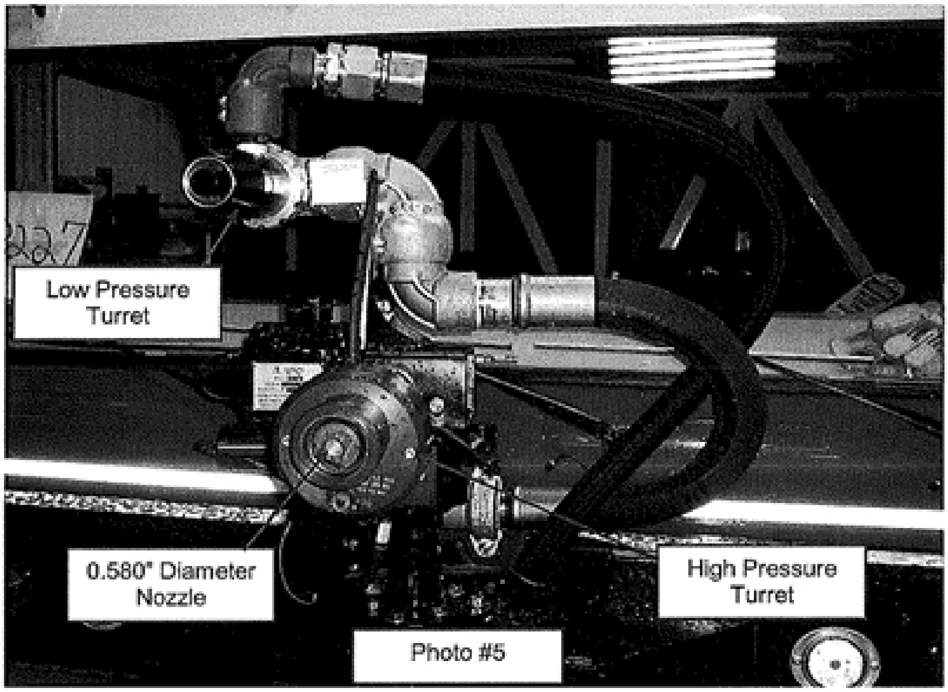

29.35
Tilt Table Platform Angle
Measurement In Degrees
UHPW P-19 #1
Right Side Downhill @ Rollover

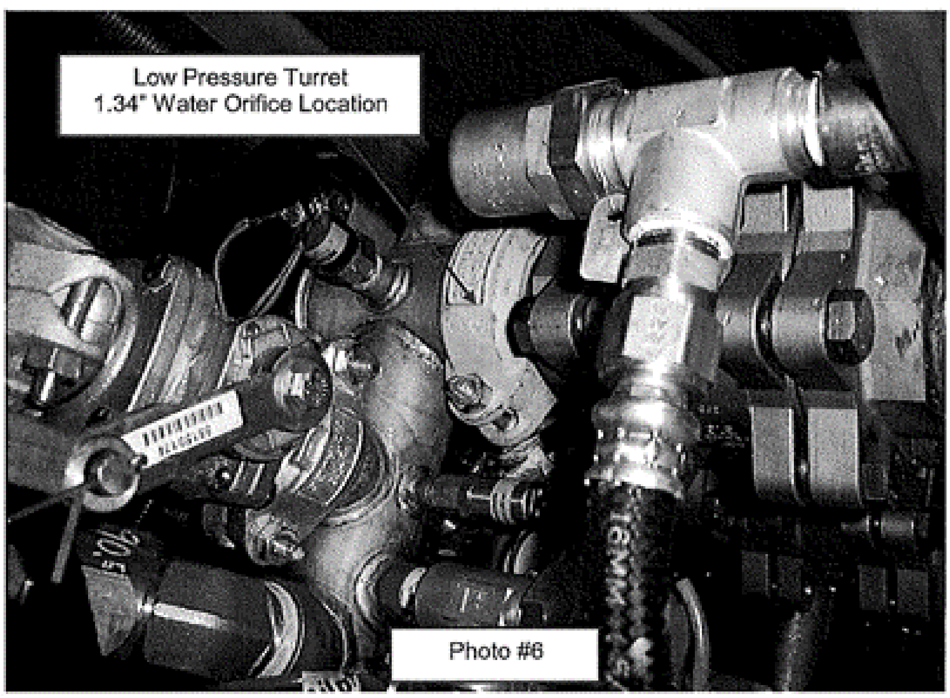

29.35
UHPW P-19 #1
Right Side Downhill @ Rollover

UHPW P-19 #1
Left Side Downhill @ Rollover



UHPW P-19 #1
Left Side Downhill @ Rollover


Low Pressure
Turret
0.580" Diameter
Nozzle
High Pressure
Turret
Photo #5


Low Pressure Turret
1.34" Water Orifice Location
Photo #6

APPENDIX D - Refractometer Calibration Curves

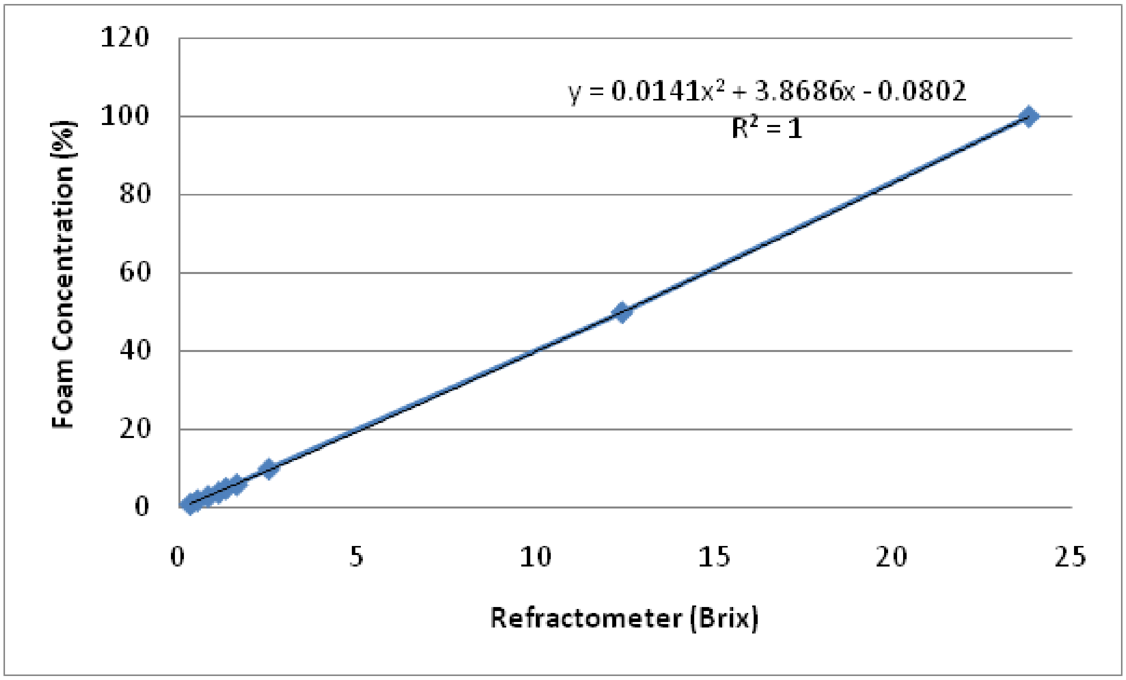


Figure D-1. Refractometer Calibration Curve for the Atago Pal-1 Using National Foam Type 3 AFFF

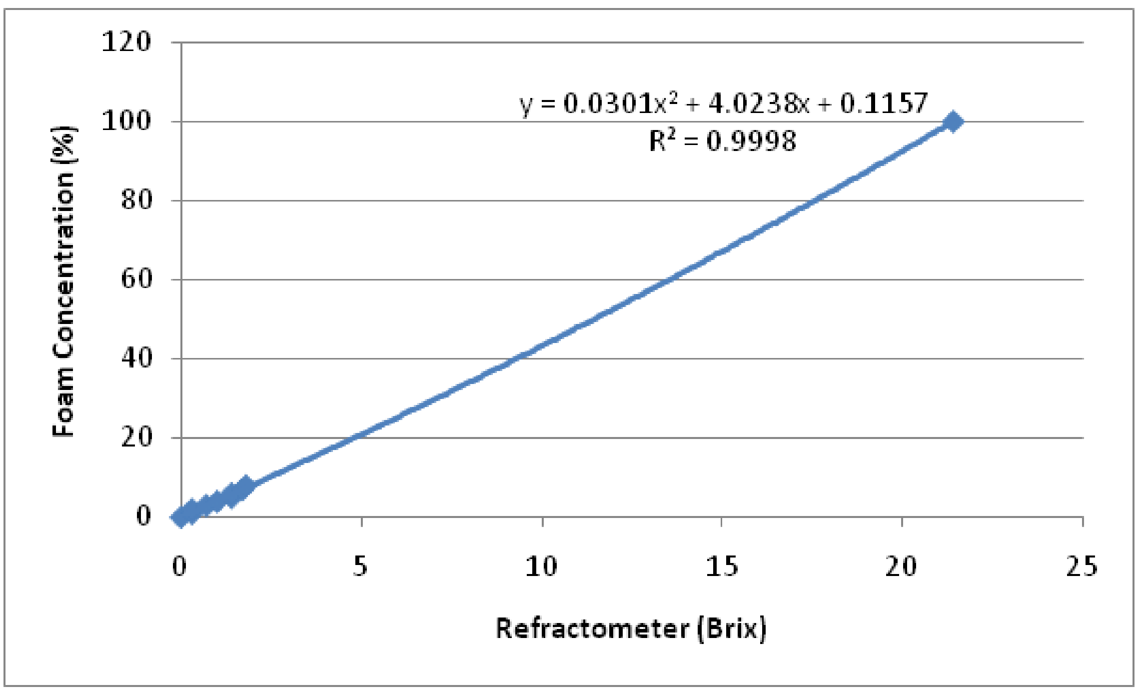


Figure D-2. Refractometer Calibration Curve for the Atago Pal-1 Using Chemguard Type 3 AFFF

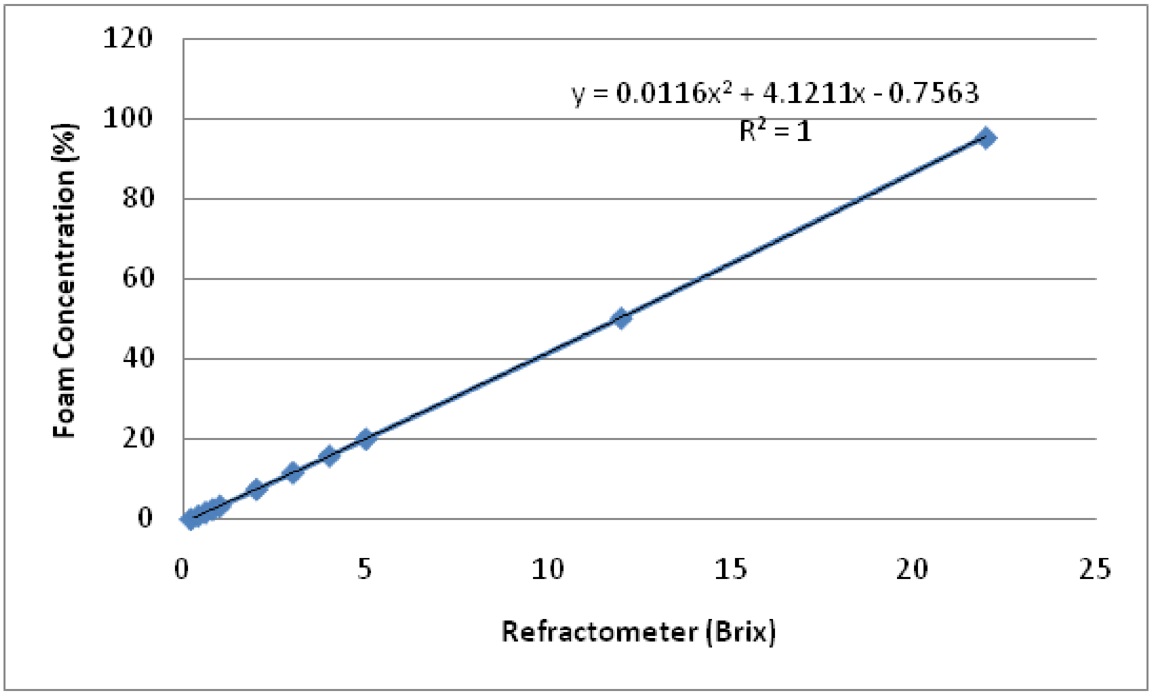


Figure D-3. Refractometer Calibration Curve for the Atago PR-32 Using Chemguard Type 3 AFFF

APPENDIX E - Phase II Field Prototype Data

Table E - 1. UHP Turret Data

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
102108_Test4	DM	26	0.020	Started fighting fire from 100+ feet back. Needed to start closer to pit.
102108_Test5	DM	25	0.019	Same as last
110708_Test1	DM	22	0.033	Good fire, no issues. Extinguished quickly.
110708_Test2	DM	11	0.0083	Smaller fire, no issues
120508_Test1	DM	13	0.0049	Small fire, quickly extinguished.
120508_Test2	DM	11	0.0041	Small fire, quickly extinguished
120508_Test3	DM	12	0.0045	Very small fire, quickly extinguished
120508_Test4	DM	18	0.014	Small fire, quickly extinguished.
112508_Test1	Dyess	42	0.013	Total extinguishment was 66 seconds but only flowed for 42 seconds. Shut flow down two times to reposition
112508_Test2	Dyess	42	0.013	Total extinguishment was 54 seconds but only discharged for 42 seconds. Shut flow down once to reposition. Took several seconds to restart discharge. Slow to move to other side of mockup
112508_Test3	Dyess	50	0.024	Total extinguishment time was 83 seconds but only discharged agent for 50. Stopped flow twice to reposition
112908_Test1	Dyess	91	0.058	Very large fire. Total extinguishment was 120 seconds but only flowed for 91 seconds. Stopped discharging three time to reposition
091608_Test2_E	Ellsworth	38	0.024	Good fire, no issues.
102808_Test3	Ellsworth	40	0.019	Good fire. Firefighter was using a quick sweeping motion from side to side, which is not the most effective method for UHP or CAF application.

102808_Test4	Ellsworth	26	0.0083	Good fire. Faster sweeping action but not as much as previous.
010609_Test2	Ellsworth	29	0.0092	Limited fire size due to ice in pit. Total extinguishment time was 44 seconds with 29 seconds of discharge.
112508_Test2_E	Ellsworth	32	0.020	Good fire, no issues.
120208_Test2	Ellsworth	40	0.013	Total extinguishment time was 75 seconds but only discharged for 40 seconds. Stopped twice to reposition vehicle.
120908_Test2	Ellsworth	27	0.0086	Smaller fire due to ice in pit. Firefighter was very effective with technique.
091608_Test2	MH	14	0.011	Good fire, no issues
091708_Test2	MH	10	0.0039	Small fire for turret
100908_Test2	MH	21	0.012	Good fire, no issues
100908_Test3	MH	12	0.0071	Video ended before fire was out-check data sheet for time
102208_Test1_MH	MH	22	0.013	Good fire, no issues
102208_Test2_MH	MH	38	0.022	Little trouble getting last fire out in rocks
102308_Test1_MH	MH	28	0.022	Good fire. Firefighter stopped short of the fire and could have extinguished more quickly if he continued application toward the back of the pit.
102808_Test1_MH	MH	19	0.015	Good fire, no issues
102808_Test2_MH	MH	20	0.012	Good fire, no issues
050508_Test1	Tyndall	31	0.024	First fire with UHP P-19c once delivered from OTC
050508_Test2	Tyndall	36	0.029	Fire with Gen Eulberg at controls
050608_Test1	Tyndall	43	0.034	Good fire, no issues
050608_Test2	Tyndall	35	0.028	Good fire, no issues
061708_Test1	Tyndall	41	0.032	Little fire left burning in rocks on side of fuselage
061708_Test2	Tyndall	32	0.025	Good fire, no issues
061708_Test3	Tyndall	31	0.022	Wind pushed fuel toward tail. Small area not involved at the nose
061708_Test4	Tyndall	24	0.019	Good fire, no issues
062708_Test1	Tyndall	25	0.020	Good fire, no issues

062708_Test2	Tyndall	39	0.031	Good fire, no issues
070108_Test1	Tyndall	27	0.016	Small area near tail that was not involved
070208_Test1	Tyndall	31	0.018	Quarter section behind wing, near tail not involved
070208_Test2	Tyndall	31	0.024	Good fire, no issues
070208_Test3	Tyndall	51	0.040	Good fire, no issues
071608_Test1	Tyndall	40	0.031	Good fire, no issues
071608_Test2	Tyndall	36	0.028	Good fire, no issues
071608_Test3	Tyndall	39	0.031	Good fire, no issues

Table E - 2. CAF Turret Data

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
102208_Test6	DM	66	0.075	Firefighter spent first 60 seconds fighting fire from side of pit that was not involved. He needed to advance to the side of the aircraft that was on fire. Discharged over 45 seconds of agent in an area that wasn't on fire.
120508_Test7	DM	24	0.018	Small fire, no issues
120508_Test8	DM	21	0.016	Small fire, n0 issues
102208_Test5	DM DM	41	0.046	Good fire, seemed little windy
092308_Test2	Ellsworth	62	0.020	Stopped flow to reposition vehicle. Total time was 74 seconds but only discharged for 62.
102308_Test3_MH	MH	26	0.020	Same as 102308_2 with small fire on opposite side of mockup in rocks.
111108_Test1	MH	62	0.049	Good technique in beginning then turret operator continued to apply agent to side of pit that was already extinguished. Appeared as though operator was trying to push foam to other side of pit to extinguish.
121608_Test2	Tyndall	57	0.045	Started out attacking fire using raindrop method. Paused agent application for several seconds to reposition truck around tail.
121708_Test3	Tyndall	101	0.060	Good fire. Stopped discharge twice to reposition vehicle.
121808_Test2	Tyndall	40	0.031	Good fire, no issues
121808_Test4	Tyndall	49	0.039	Good fire, no issues

Table E - 3. Hydro-Chem™ Turret Data

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
110708_Test3	DM	18	0.020	Video cut off right at end. Probably fought fire for another 1-3 seconds.
110708_Test4	DM	18	0.014	Smaller fire, no issues
120508_Test5	DM	26	0.010	Small fire. Seemed to have problems extinguishing the back.
120508_Test6	DM	14	0.011	Small fire but good extinguishment
093008_Test2	Ellsworth	32	0.010	Had to stop to reposition vehicle because of problems with Hydro-Chem™ turret not moving full left. Total time was 61 seconds with 32 seconds of agent flow.
100708_Test2	Ellsworth	60	0.010	Staged truck on opposite side of pit and did not advance until 20 seconds into the fire. Repositioned the vehicle, then began fighting fire again after another 20 seconds
102308_Test2_MH	MH	39	0.031	Good fire. Did not count last 16 seconds as they were trying to put out a small fire in the rocks on the other side of the mockup. Probably could have extinguished quicker if they repositioned the truck.
121608_Test1	Tyndall	31	0.018	Good fire, no issues
121708_Test1	Tyndall	40	0.031	Good fire, good extinguishing technique.
121808_Test1	Tyndall	77	0.061	Good fire. Stopped twice to reposition vehicle.
121808_Test3	Tyndall	63	0.037	Good fire, no issues

Table E - 4 UHP Handline Data

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
102108_Test1	DM	14	0.00035	Small fire, quickly extinguished
102108_Test2	DM	26	0.00065	Very windy, small fire, extinguishment took longer
102108_Test3	DM	100	0.0025	Very windy, third fire that day with a lot of fuel built up in rocks. Firefighters fighting fire from side so some fire pushing back toward them. Issues with gloves and heat from fire. In this case, the UHP handline was overwhelmed by the fire
120108_Test1	DM	76	0.0057	Large fire that spread from front to back. Note that no foam blanket is seen in the video even after 76 seconds of application. Curios about foam concentration for that fire. Might have needed to be a little more aggressive with the fire like next CAF fire
120108_Test3	DM	15	0.00038	Small fire, quickly extinguished
011409_Test1	Dyess	59	0.0013	Firefighters did not keep agent flowing consistently but kept turning on and off. This contributed to the extended extinguishment time.
011409_Test2	Dyess	89	0.0019	Firefighters kept shutting off agent, looking around the pit, stopping to get guidance from others, sweeping rapidly, going from fog to straight stream. Video ended before fire was extinguished. Total time was 126 seconds but only flowed for 94 seconds.
011409_Test3	Dyess	110	0.0047	Very large, full pit handline fire. Firefighter continued to flow agent the entire time and used slow sweeping method. Extinguishment was greatly enhanced compared to first two fires.

011409_Test4	Dyess	139	0.0059	Very large fire. Different firefighter than first three fires. Continuous flow of agent with the exception of twice when agent was turned off. Firefighter added time by criss-crossing pit and applying agent to rocks that had already been extinguished.
091608_Test1_E	Ellsworth	103	0.0033	Large fire. Stopped after 35 seconds then resumed fire fighting after another 23 seconds. May have had issues with foam as this was the first fire with the vehicle.
102808_Test1	Ellsworth	43	0.00091	Good handline fire. Good technique. Fire on both sides of mockup.
120208_Test1	Ellsworth	100	0.0021	Large fire. Wind pushed fuel to opposite side of pit. Total extinguishment time was 116 seconds with 100 seconds of discharged. Stopped once to reposition.
120908_Test1	Ellsworth	87	0.0018	Good fire. Longer extinguishment time due to ice in pit, which made footing difficult.
091608_Test1	MH	52	0.0020	First handline fire. Good fire coverage
091708_Test1	MH	22	0.00058	Smaller fire than others
100408_Test5	MH	66	0.0026	Fire in rocks taking several seconds to extinguish. Pool fire extinguishing quickly.
100708_Test1_MH	MH	52	0.0020	Using an aggressive, fast sweeping motion. Spent several seconds trying to get fire out from around one wheel.
012109_Test1	Tyndall	54	0.0014	Good fire, no issues
012109_Test2	Tyndall	63	0.0017	Good fire. Wind and agent stream pushed fuel to other side of mockup. Only fire on test side was counted.
012109_Test3	Tyndall	51	0.0013	Good fire, no issues
012109_Test4	Tyndall	63	0.0017	Good fire, no issues

Table E - 5. CAF Handline

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
102208_Test1	DM	48	0.0054	Good fire, no issues
102208_Test2	DM	15	0.00085	Small fire, extinguished quickly
120108_Test2	DM	24	0.0027	Good fire, good sweeping action. Quickly extinguished.
011409_Test5	Dyess	87?	0.0083	Very large fire. Video ended before fire was extinguished. Video ended after 87 seconds. The data was included since only CAF handline from Dyess.
092308_Test1	Ellsworth	77	0.0037	Good fire, no issues.
102808_Test2	Ellsworth	63	0.0030	Good fire on both sides of mockup. Primary firefighter had a problem after extinguishing first half and delayed advancing to other side for several seconds.
110408_Test1	Ellsworth	59	0.0014	Small fire. Started fire fighting from opposite side of pit not involved, which didn't give them a lot of hoseline to reach the other side where the fire was located.
100408_Test3	MH	39	0.0034	Fire in rocks took several seconds to extinguish. Pool fire extinguished quickly.
100408_Test4	MH	45	0.0040	Fire in rocks took several seconds to extinguish. Pool fire extinguished quickly.
100708_Test2_MH	MH	57	0.0050	Spent several seconds on each wheel. Video is zoomed in to close so can't see exactly what they are doing
100708_Test3_MH	MH	46	0.0041	Can see difference in difficulty to handle CAF versus UHP handline
012309_Test1	Tyndall	48	0.0014	Small fire, no issues
012309_Test2	Tyndall	53	0.0031	Good fire, no issues
121908_Test2	Tyndall	42	0.0025	Good fire. Can see how hard nozzle is to control.
121908_Test4	Tyndall	41	0.0024	Good fire. Better control of nozzle.

Table E - 6. Hydro-Chem™ Handline

Date_Test	Location	Ext Time (sec)	Appl Rate (gal/sq ft)	Comments
102208_Test3	DM	25	0.0014	Good fire, small but extinguished quickly
102208_Test4	DM	33	0.0037	Good fire, trouble with fuel in rocks
120108_Test4	DM	8	0.00045	Very small fire, quickly extinguished
120108_Test5	DM	10	0.00057	Very small fire, quickly extinguished
093008_Test1	Ellsworth	82	0.0039	Good fire. Sun in video makes image difficult to view.
100708_Test1	Ellsworth	30	0.00072	Firefighters start on edge of pit and take several seconds to enter pit and get agent on the fire
112508_Test1_E	Ellsworth	139	0.0066	Large fire. Total extinguishment time was 268 seconds with 139 seconds of agent discharge. Stopped flow twice to reposition, once to fix a kink in hose and once to move truck because not enough hoseline to reach other side of pit.
121808_Test1_E	Ellsworth	52	0.0025	Very cold with snow and ice.
100408_Test1	MH	16	0.00094	Hydro-Chem™ makes it difficult to see exactly when the fire was extinguished
100408_Test2	MH	30	0.0027	Video ended before fire was completely out. Extinguishment was probably around 30 seconds. Firefighters having more difficult time with this fire than previous
100708_Test4_MH	MH	32	0.0028	Firefighter would turn off agent to advance. Actual fire fighting time was 48 seconds but 16 seconds were spent advancing without discharging agent.
100708_Test5_MH	MH	65	0.0057	Same as last but only stopped discharging for 7 seconds to advance.
100908_Test1	MH	130	0.011	Intense fire. Firefighters had difficult time extinguishing. Resembled a fire with dry chemical and no foam. Firefighters getting a lot of burnback.

121908_Test1	Tyndall	29	0.00085	Small fire. First handline for Firefighter Pierce. Can see how hard nozzle is to control.
122308_Test1	Tyndall	35	0.0021	Good fire, no issues
122308_Test2	Tyndall	32	0.0019	Good fire, no issues
122308_Test3	Tyndall	71	0.0042	Firefighter tripped and fell twice. Stopped discharging after 71 seconds before fire was completely extinguished.
122308_Test4	Tyndall	35	0.0021	Good fire, no issues.

ACRONYMS

AFFF	Aqueous film forming foam. Primary fire fighting agent used to extinguish hydrocarbon fuel fires.
AFRL	Air Force Research Laboratory.
AFRL/RXQD	Air Force Research Laboratory, Deployed Base Systems Branch.
ARFF	Aircraft Rescue and Fire Fighting. Refers to fire fighting operations related to any type of aircraft including fixed wing and rotary.
CAF	Compressed Air Foam.
COTS	Commercial-off-the-shelf.
CRADA	Cooperative Research and Development Agreement. It is a formal written agreement between a private company and a government laboratory to work together on a project.
D	Dyess Air Force Base, Texas.
DC	Dry Chemical.
DM	Davis-Monthan Air Force Base, Arizona.
E	Ellsworth Air Force Base, South Dakota.
FEET	Fire Extinguishing Effectiveness Testing. Test series completed by AFRL/RXQD documenting the effectiveness of UHP, CAF, low pressure and dual agent fire fighting systems.
FRE	First Response Expeditionary fire vehicle. This was the first UHP system developed by AFRL/RXQD in 2002.
gsf	Gallons per square foot. Unit of measure used to define the effectiveness of a particular fire fighting system, such as UHP.
HQ AFCESA	Headquarters Air Force Civil Engineering Support Agency.
gpm	Gallons per minute.
MH	Mountain Home Air Force Base, Idaho.
MIL SPEC	Military Specification.

NFPA	National Fire Protection Association.
psi	Pounds per square inch.
R&D	Research and Development.
T	Tyndall Air Force Base, Florida.
TD	Technology Demonstrator. The TC is a T-3000 fire truck used by Oshkosh to build working prototypes of new fire fighting system designs.
TO	Technical order.
scqm	Standard cubic feet meter.
UHP	Ultra High Pressure. Fire fighting technology that operates above 1100 psi.
UHP P-19c	Ultra High Pressure P-19 converted with single centrifugal pump.
UHP P-19p	Ultra High Pressure P-19 converted with three plunger pumps.

GLOSSARY

The majority of these terms are defined precisely according to National Fire Protection Association (NFPA) 412[1].

Aqueous Film Forming Foam (AFFF) Concentrate – A concentrated aqueous solution of one or more hydrocarbon or fluorochemical surfactants that forms foam capable of producing a vapor-suppressing aqueous film on the surface of hydrocarbon fuels (NFPA 412).

Burn back – Fire spreading to areas previously extinguished.

Centrifugal Pump UHP P-19 (UHP P-19c) – Ultra high pressure P-19 designed with a new six-stage centrifugal pump designed by W.S. Darley & Co to operate at 300 gpm. This pump was used in the five modified P-19s used for field evaluation.

Compressed Air Foam (CAF) – Using compressed air in conjunction with a water/AFFF foaming solution to produce foam with an expansion ratio of 5:1 or greater (NFPA 412).

Dry Chemical (DC) – A potassium bicarbonate based chemical powder that is used to extinguish Class B liquid fuel fires.

Foam – Fire fighting foam is a stable aggregation of small bubbles of lower density than oil or water that exhibits tenacity for covering horizontal pool fires. Air foam is made by mixing air into a water solution, containing a foam concentrate, by means of suitably designed equipment. It flows freely over a burning liquid surface and forms a tough, air-excluding, continuous blanket that seals volatile combustible vapors from access to air. It resists disruption from wind and draft over heat and flame attack and is capable of resealing in case of a mechanical rupture. Fire fighting foam retains these properties for relatively long periods of time (NFPA 412).

Foam Drainage Time (Quarter Life) – The time in minutes that it takes for 25 percent of the total liquid contained in the foam sample to drain from the foam (NFPA 412).

Foam Expansion – The ratio between the volume of the foam produced and the volume of solution used in its production (NFPA 412).

Plunger Pump UHP P-19 (UHP P-19p) – Ultra high pressure P-19 designed, fabricated and tested by AFRL in 2005 using three 100 gpm CAT plunger pumps. This vehicle demonstrated that the 300 gpm UHP technology was a viable replacement for larger 500 gpm low pressure systems.

Technology Demonstrator (TD) – An Oshkosh T-1500 aircraft rescue and fire fighting (ARFF) vehicle used by Oshkosh Corporation to design, fabricate and test prototype fire fighting systems.

Type 3 – AFFF to be used at 3 parts concentrate to 97 parts water by volume[2].

Ultra High Pressure (UHP) – Water/AFFF applied at pressures between 1,100-1,500 pounds per square inch (psi).